Universidade de Aveiro Departamento de Economia, Gestão, Engenharia Industrial e Turismo
Ano 2018

RUI MANUEL RIBEIRO GONÇALVES

PROJECTO DE IMPLEMENTAÇÃO DE UM SISTEMA COLABORATIVO HUMANO-ROBOT NA DIVISÃO DE PLÁSTICOS DO GRUPO SIMOLDES

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Projecto apresentado à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia e Gestão Industrial, realizada sob a orientação científica da Prof. Dra. Ana Luísa Ferreira Andrade Ramos, Professora Auxiliar no Departamento de Economia, Gestão, Engenharia Industrial e Turismo da Universidade de Aveiro.

“The good life is one inspired by love and guided by knowledge”

Bertrand Russell

o júri

Presidente	Professor Doutor José António de Vasconcelos Ferreira, Professor Associado da Universidade de Aveiro
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palavras-chave

Colaboração Humano-Robot, Indústria 4.0, Segurança na Colaboração Humano-Robot, Simulação

resumo

A Indústria 4.0 apresenta-se no presente momento às principais empresas de produção como um conceito a, obrigatoriamente, ser tomado em conta na revisão dos seus processos produtivos. Este conceito, assenta essencialmente na integração das diversas tecnologias de informação e comunicação e soluções robóticas emergentes, como a Inteligência Artificial e a Internet das Coisas e aplica-as ao ambiente industrial, levando a uma automação de processos e maior qualidade no produto acabado. A facilidade em dar resposta a variações de procura e tipos de produto de forma eficiente e baixo custo, torna este conceito extremamente atrativo, para empresas que produzam uma elevada gama de produtos diferentes, nomeadamente para o setor automóvel. Por essas razões, a Europa olha para a Indústria 4.0, como uma forma de revitalização do seu setor produtivo, que decaiu com o aparecimento de mercados mais competitivos, como por exemplo, o Médio Oriente ou a China, e aposta em projetos de pesquisa e desenvolvimento relacionados com este conceito. O projecto desenvolvido neste documento, inserido numa iniciativa de âmbito europeu, tem como objetivo, a criação de uma proposta devidamente sustentada para uma solução colaborativa entre operadores humanos e robôs colaborativos, um dos pilares da Indústria 4.0, num contexto fabril, numa das empresas da Divisão de Plásticos do Grupo Simoldes. Para tal, será apresentado o trabalho realizado num estágio de nove meses correspondente ao primeiro de três anos da duração do projecto, que consistiu essencialmente na definição dos casos de aplicação, no levantamento e formulação das considerações de segurança a ter conta ao implementar uma solução deste cariz na empresa, e de um estudo de simulação para as novas linhas de produção de forma a sustentar a proposta criada. O trabalho apresentado espera assegurar uma transição suave e uma implementação eficaz de um novo paradigma de produção para a Simoldes Plásticos, que pretende aumentar a eficácia das suas linhas de produção e adaptar-se a um mercado cada vez mais exigente.

keywords

Human-Robot Collaboration (HRC), HRC Safety, Industry 4.0, Simulation

abstract

Industry 4.0 presents itself to the main manufacturing companies as a priority subject to consider, while reviewing their productive processes. This concept, stands essentially on the integration of the diverse emerging information and communication technologies and robotic solutions, with Artificial Intelligence and the Internet of Things as examples, and the respective application into the factory context, leading to more autonomous processes and increased quality on the product delivered. The simplicity in providing an efficient and low-cost response to nowadays market variations, makes this kind of solutions highly attractive to companies, which have a long range of products with different lot sizes and production complexity levels, such as the automobile industry. For those reasons, Europe is growing an interest Industry 4.0, to revitalize and boost their Manufacturing sector, which has decline due to the growth of more competitive markets such as China and the Middle East, investing in research and development projects related with it. Throughout this document, it will be presented a project, inserted in an European funded initiative, that aims to propose a well-sustained solution for a human-robot collaboration production cell in an industrial environment, within one of the Simoldes Group-Plastic Division factories. To achieve it, in this document will be presented the work developed in a nine-month internship during the first year, out of three, of the project length that consisted in the definition and evaluation of two application cases, the formulation of safety considerations that the company should mind while implementing this kind of solution, and a simulation study for the new production lines, to properly sustain the created proposal. The work developed in this document expects to ensure a smooth to a new production paradigm for Simoldes Plásticos, that pretends to bring more efficiency to its production lines and to adapt itself to a constantly demanding market.

List of Abbreviations:

AGV	Autonomous Guided Vehicle
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
EU	European Union
FoF	Factories of the Future
GDP	Gross Domestic Product
HRC	Human-Robot Collaboration
INESC TEC	Instituto de Engenharia de Sistemas e Computadores, Tecnlogia e Ciência
KPI	Key Performance Indicator
MES	Manufacturing Execution System
OSPS	Open Scalable Production System
PPP	Public Private Partnership
SP	Simoldes Plásticos
OEM	Original Equipment Manufacturer

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Chapter 1: Introduction

1.1 Contextualization

It is no longer an absurd to say that we live in the dawn of a new industrial revolution. The exponential advances on technology that we assisted in the last decades had significantly changed the way people interact with each other, lifting barriers and ignoring borders, bringing everyone and everything closer, creating a huge impact in our daily life. In the industry field, this "technology cavalcade" is also being felt, and companies must be extremely updated, with the risk of being obliterated by the competition. Throughout the last years, we have seen concepts such as "Human-Robot Collaboration", "The Internet of Things", "Big Data" or "Industrial Simulation" being brought frequently to the spotlight, always, under the umbrella of the term that is in everyone's mouth: Industry 4.0.

Industry 4.0 was the term that the Germany Academy of Sciences, *Acatech*, gave to the integration off all the mentioned technologies in the companies productive process, and it represents not just a major trend, but a complete paradigm shift, a true industrial revolution, therefore, the terminology "4.0". (Kagermann, Wolfgang, & Helbig, 2013)

Also, due to the emergence of competitive markets in Asia, Europe's industry has been declining for the past years, having a way weaker position within the European Union GDP. Facing this situation, the EU looks now to Industry 4.0 as a path to revitalize its industry, promoting and funding projects that stimulate universities and companies to investigate and adopt, respectively, this kind of technological integration. (Blanchet, Rinn, & Von Thaden, 2014)

Currently, the scenario is more critical to companies that deal with a wide range of products with even shorter cycles and market variations, such as the automotive industry, which must update their process and technologies to not be left behind. In the last years, we have seen major brands in the sector adopting Industry 4.0 related ideas, especially in the field of autonomous and collaborative robots.

It is in this scenario that Simoldes Group – Plastic Division, a company that produces plastic injected components, mostly for the automotive sector, is included. Simoldes is currently facing production issues regarding an increase in their product demand, and consequently, needs to adapt their processes to become more flexible and efficient.

1.2 Objectives

To adapt themselves to this scenario, and develop an efficient solution, Simoldes has joined the European funded project, Scalable 4.0, alongside other industrial and academic partners spread across Europe, that consists in the implementation of an autonomous and collaborative robotic solution to address this technological demand.

The project itself, it's still under an early stage of development, so the focus of the nine-month internship, in which the personal work developed in this document was done, stand on a deep analysis and study of the current production paradigm of Simoldes, be the main connection between the company and the research partners of the project and to provide the solutions to best prepare the company for the upcoming implementation.

For that purpose, there were three goals for this project: Specifically define the application cases on which the Scalable project should be applied into, and analyse it to find the most suitable improvement points that could benefit from it, as to gather all the useful information regarding it. To perform a Risk Assessment to represent all the dangers associated with this new technology to be implemented at a Simoldes plant as to come up with a concrete and clear Risk Prevention Plan, and finally, to visually represent what the new production lines would look like, and to retrieve the inherent conclusions to draft an action plan for the months to come.

1.3 Structure of the document

The second chapter of this Master Thesis will explain in detail, through a literature review, the current state-of-the-art, when it comes to Industry 4.0, as well as two of its main pillars: Human-Robot Collaboration, with the resource of recent application cases of its implementation performed by well-known companies, along with the required safety measures to be considered, and the Industrial Simulation, where it will be presented the evolution of simulation until today, and how to select the best simulation technique to approach the problem into study. In Chapter 3, the same concepts will be illustrated in a case study based on a nine-month internship at Simoldes Plásticos in an Industry 4.0 related project, explaining the methodology adopted and presenting the expected results, aided by an Industrial Simulation software, Simio, as well as a proposal of a new paradigm for a production line in Plastaze, one of the factories of the group.

Chapter 2: Industry 4.0 The Industrial Revolution of the 21st Century

2.1 Defining the concept of Industry 4.0

The end of the XVIII century had marked one of the most breakthrough moments in the History of the World. The invention of the steam power machine triggered the mechanization of processes and had ignited the Industrial Revolution. Almost one century after, the electrification of the factories opened the way for the first assembly lines for mass production, and in the second half of the XX Century, mankind assisted the dawn of computers and new automated solutions that changed the way that organizations looked at their workstations. Looking back, it is possible to notice that all this three key moments in Industry had one thing in common: They were enabled by main technological and ideological disruptive advancements and had resulted in main productivity gains in the industrial sector (Rüßmann et al., 2015).

Nowadays, the world is living in the advent of a reality becoming each day more and more attached to digital technologies that started to be developed with the coming of the new millennium, and had already assisted the beginning of a new industrial revolution which is resulting again into major production paradigm shifts that experts had baptized as Industry 4.0 (Kagermann et al., 2013). This movement, that have started in Germany, is defined by the combination and integration of technologies, such as the ones we can see from Figure 1, that although already existed for several years, are now reaching a state of maturity, that allows the creation of **Cyber-Physical Systems (CPS)**.

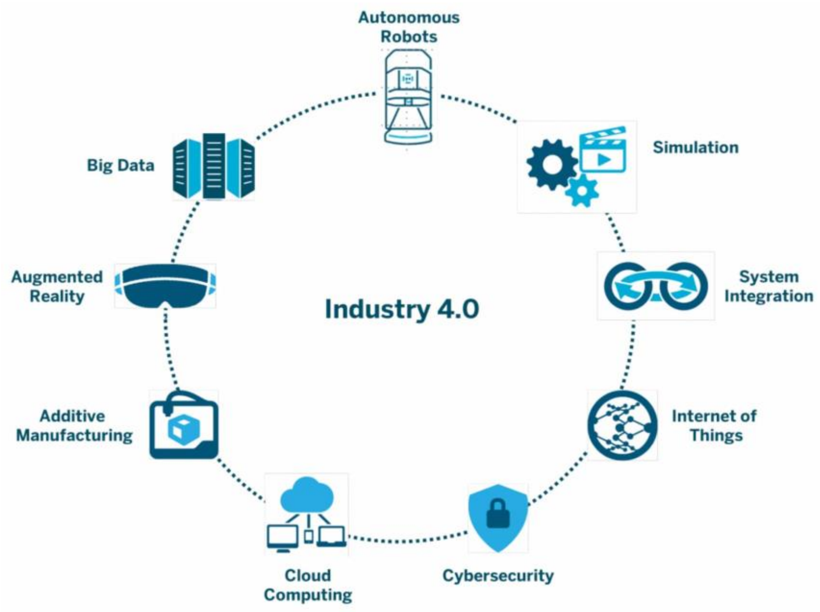

Figure 1 "The 9 pillars of Industry 4.0",
(Source: https://www.semiwiki.com/forum/content/6341-industry-4-0-manufacturing-processes.html)

Cyber-Physical Systems (CPS) are the basic unit of the Industry 4.0 concept and its defined by the integration of both physical and digital worlds by embedding physical objects with software and computing power able to self-manage with themselves. These systems will turn then the manufacturing equipment as **CPPS, Cyber-Physical Production Systems,** machinery that when geared with sensors and actuators and an embedded software, is able to know their own status, performance and configurability, to take decisions on their own. (Almada-Lobo, 2016), It reduces the human error and the set-up times for the production processes, triggering significant changes in the manufacturing production towards a complete decentralized system, ensuring that only efficient operations would be conducted. Also, according to Almada-Lobo's opinion and many other experts, most companies, still live in a dark age, when it comes to efficiency and quality, and should take a careful step-by-step approach, such as implementing a MES system and other related operations management practices, before fully implementing autonomous CPS networks.

The application of a CPS, approaches the three dimensions of the Industry 4.0 paradigm which are the horizontal integration across the entire value chain network, an end-to-end engineering across the whole product life cycle and the vertical integration and network of manufacturing systems. A way to understand these dimensions is by looking to Industry 4.0 from a micro and a macro perspective (Stock & Seliger, 2016).

The **macro-perspective** covers the horizontal integration and the end-to-end engineering dimensions. The horizontal integration is characterized by a network of value creation modules sustained by an exchange of different value creation factors. The linkage between them leads to an intelligent network covering the value chains of the product life cycles and the uprising of new and innovative business models. The relationship between this integration and the CPPS would result in more highly transparent and integrated supply chains by permanently mapping the physical flows on digital platforms (Almada-Lobo, 2016).

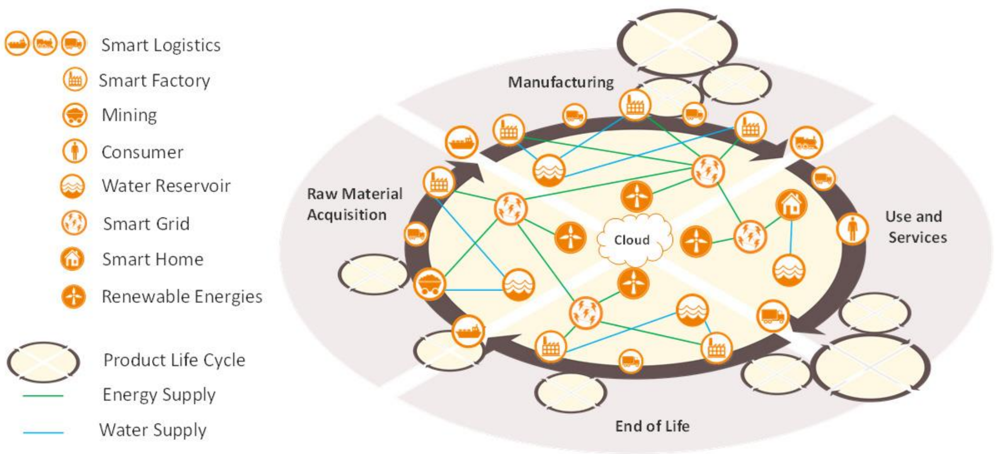

Figure 2 Macro-perspective of Industry 4.0 (Source: Stock & Seliger, 2016)

The **micro-perspective** of Industry 4.0 focus essentially in the factory's environment and covers both horizontal and vertical integration within it, and is a part of an end-to-end engineering dimension as well. In a micro-perspective, the crossing of the value creation modules is made along the material flow of the factory, due to the implementation of smart logistics. **Smart Logistics** are characterized as using transport resources that can agilely respond to unforeseen events such as congestions in the factory traffic and can operate autonomously. The most common examples are AGV's, that are most used for in-house transportation along the material flow. Within the plant, the AGV's would also be connected to other smart technologies such as advanced intelligent robots, sophisticated sensors, Cloud computing, smartphones and other mobile devices trough an interoperable global value chain, that could be shared by different stakeholders and factories all over the world, connecting both physical and virtual worlds (Geissbauer, Vedso, & Schrau, 2016).

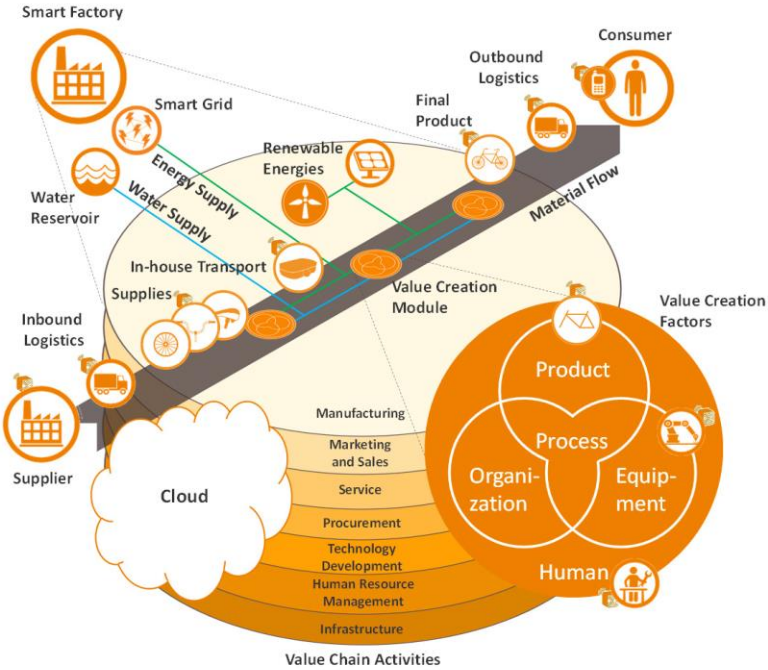

Figure 3 Micro-perspective on Industry 4.0 (Source: Stock & Seliger, 2016)

All these paradigm changes created big shifts in the way manufacturers look now to the product life cycle. In Industry 4.0, the product design and development take now place in simulated labs, taking only form, once most of the engineering problems or other design problems are solved. The same applies not just for the products, but also for the process and layout changes as well. The main results are translated into significant cost savings that comes from the resultant efficiency and the technologic integration, which allows support real-time quality control and maintenance, smooth operations and to reduce breakdowns.

If during the second Industrial Revolution, due to the electrification of the plants, companies started to mass produce their products, now, within the Industry 4.0 context, we'll assist a **mass customization.** This means that companies are now able to produce fully tailored products according to the customer's requirements with the same cost, as they would mass-produce the same product back in the 20th Century, resulting in revenue gains (Geissbauer et al., 2016).

According to a study from PwC in 2016, the **adoption of advanced levels of digitalization and integration**, **within the surveyed companies from the Industrial Manufacturing sector was about 35%**, a number that is expected to grow to **76% by 2020.** Also for the record, around **86% of the respondents expected to see both cost reductions and revenue gains from their digitalization efforts** and about **a quarter of them expect to see those improvements exceed 20% in the following 5 years**, while 55% of them expect to see their investment returned in a couple of years, which is a short time based on the capital required (PwC, 2016).

According to Geissbauer *et al* (2016)., for a company to approach an Industry 4.0 digitalization integration, there are three main aspects they should follow:

1. **Full digitalization of a company's operations:** A company should go for a technological integration both vertical and horizontal. For example, the company should start think about the design of flexible fabrication facilities, supported by programmable robots to perform most of the hard-working/repeatable operations and start prototyping new assembly lines in a dedicated software before turning them into reality. This way, the company could almost effortless, simulate a new plant design, testing it for flaws, and only investing on physical machinery only when it is clear it's efficient, turning the process of bringing new products to the market and test new offers, leaner and less expensive.
2. **Redesign of products and services,** to be embedded with custom-designed software to become more responsive and interactive, so they're able to track their own activity and results in real-time, as the other products around them. At an Industry level, this would provide insights on how they operate, where they face delays or on how they work around problems.
3. **Closer interaction with customers:** Due to the information and communication technologies advancements and enabled by the new processes, products and services, the value chains can and should be now able to be more responsive and interactive, allowing industrial manufacturers to reach end-customers' needs more directly and tailor their business models accordingly.

Still, it is consensual by most of the authors and experts on the Industry 4.0, that the bigger challenge that stands in front of most companies, especially in countries like Portugal, are not related with the adoption of new and advanced technologies, but instead on a major shift in the organizational practices and culture for them to be more digitally oriented and more interconnected between each functional area.

2.2 Europe's Perspective on Industry 4.0

Nowadays, most of traditional industrialized countries have been dealing with a decline within the manufacturing environment due to three main factors: major productivity gains achieved in mature economies, the loss of market share to emerging countries and the outsourcing of activities such as logistics, maintenance and other different types of professional services to the service industry, which led to the relocation of the activity itself (Blanchet et al., 2014).

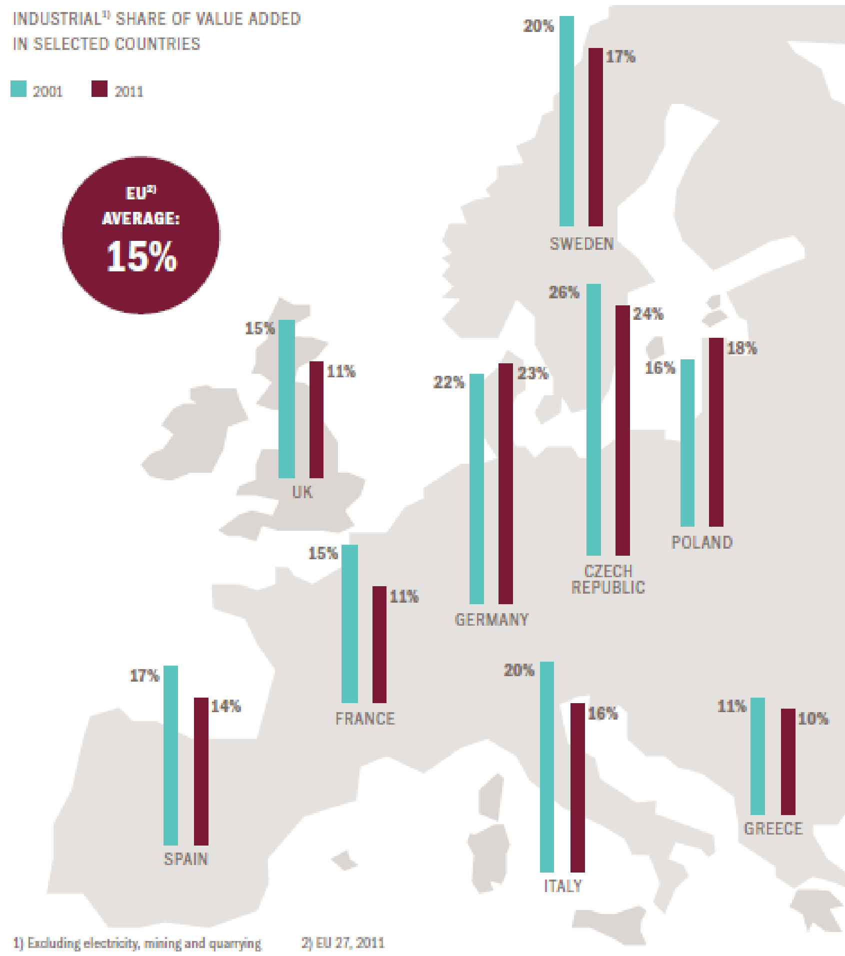

Figure 4 Industrial Share of Value added in selected countries (Source: Blanchet et al., 2014)

To maintain its competitive edge facing new emergent economies, Europe should take advantage of Industry 4.0 technological advancements by se**lecting high value products and activities**, **having modern and automated production units** and by **implementing manufacturing excellence practices such as Lean Management** (Blanchet et al., 2014). For it for happen, it is crucial that Europe should act immediately, and consequently, European Union had set the goal of boosting EU's manufacturing's share from 15% to 20% by 2020, which would translate in 500 billion euros created in added value and 6 million jobs in this sector.

Seeing its position has industrial power house eroding and its leadership in many important manufacturing sectors constantly being challenged by new emergent economies, European Commission has launched in 2008, the PPP for Factories of the Future of the Future (FoF) under the European Economic Recovery Plan. This PPP had gather until 2013 150 high level projects that joint efforts of top industrial companies and research and academical institutions in Europe. From 2014 to 2020, the FoF roadmap sets a vision and outlines routes towards for high added value manufacturing technologies, which should be clean, highly performing, environment friendly and socially sustainable, expecting to deliver technologies to create more sustainable and competitive factories within the European Union (European Commission, 2014).

One of the many European funded projects under the umbrella of the FoF PPP was the STAMINA project (Sustainable and Reliable Robotics for Part Handling in the Manufacturing Automation), that settled the final goal of developing and experimenting a mobile robotic system to perform preparation and distribution operations for pieces "kits" in the automotive industry. The project, in resemblance to the one which will be the focused of this thesis, had gathered partners from both academia and industry, having PSA Peugeot-Citroën (France) as end-users. The results of the project were a reduction of musculoskeletal disorders for the operators, more competitiveness of the production sites and an increased response to the growing customer demand for vehicle customization (BA Systems, 2017).

2.3 Human-Robot Collaboration (HRC)

2.3.1 HRC: Definition and Context

Human-Robot Collaboration (HRC) has been a concept that have been object of study over the last decade, and due to its potentialities, has been one of the most prominent examples of the Industry 4.0 pillar technologies. Although the concrete the definition of HRC is still in hot debate by most authors, and has evolved with time as technology gets refined, the main idea behind it, is to have both human and robotic resources working in the same workspace, to achieve a common goal. This way, the productivity of system is increased by combining the flexibility and ability to perform multiple tasks of a human worker, and the precision, strength and other potentialities of an automated robot.

The first collaborative robots have been introduced by Edward Colgate, when presented a simple "*cobot*" with one simple joint and two control modes, that could provide guidance to human operator's motion. (Colgate, Wannasuphoprasit, & Peshkin, 1996). Later, in the beginning of the 21st century, Helms developed the assistant "*rob@work"* that provided a flexible device with direct interaction, equipped with 3D sensors, (Helms, Sehraft, & Hägele, 2002), and years after, come up with PowerMate, an assistant robot with components suitable for industrial use for the handling and assembly tasks (Schraft, Meyer, Parlitz, & Helms, 2005).

Currently, we're assisting to quick developments in the manufacturing technology, with product life cycles getting shorter and the mass production paradigm shifting to a mass customization one. This means that companies should concern on adapting their production systems to be more flexible, dynamic and with shorter cycle times, to able to deal with an increasing product variation, which gets critical in the automotive sector. The principal drawback, is the fact that traditional robot-based solutions are not able to give the desired answer to this demand, since they have reached a bottle-neck when it comes to providing the required flexibility to deal with this era of product transformation. That's why, HRC has been considered by many authors as the answer for this problem (Too et al., 2009).

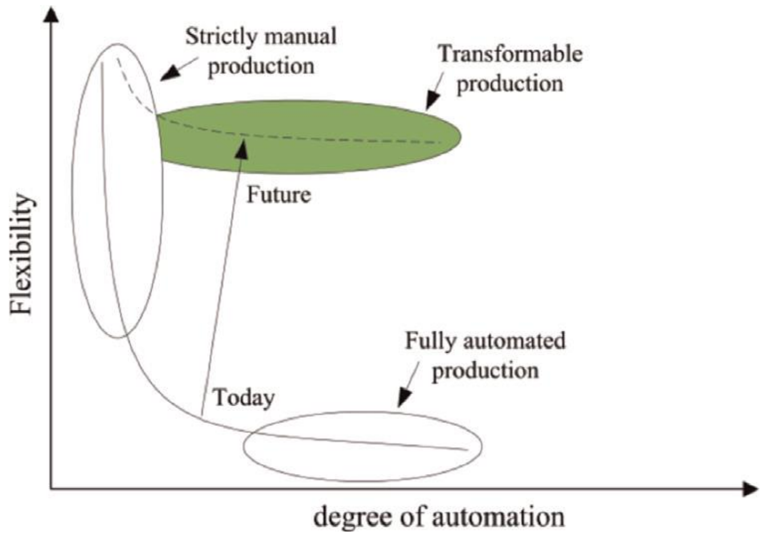

Figure 5 A requirement of the factories of the future shows a high degree of flexibility while still providing a degree of automation (Source: Rath et al., 2016)

From what is possible to retrieve from Figure 5, the current industrial manufacturing paradigm stands that the traditional manufacturing systems are automated to a large degree but with a high difficulty level on becoming more flexible, which could be brought using traditional manual labour operations, but have the counterpart of not being economically viable in large scale, especially in countries with high wages (Rath et al., 2016).

In the future, to achieve mass customization, it will be necessary to reach a level within the manufacturing companies of high reconfigurability, sustained by a large level of automation. Rath *et al*. (2016), proposes two ways to achieve it: Equipping the workers with automation tools such as intuitive on-the-fly programming of robots or the improvement of the reconfigurability level of the traditional automated lines.

Besides productivity, another main motivation for companies to implement this kind of solutions was the well-being of their employees and the ergonomics of their processes. However, the lack of flexibility, mentioned in the previous paragraphs, of the current robotic solutions, turns companies, especially in countries where the hand-labour is relatively cheap, such as Portugal, to still rely on operators to perform repetitive and unergonomic tasks. The consequences are a decrement in the collaborators motivation which ends in more quality and consistent errors, besides more absenteeism, resulted from work-related injuries.

This is a scenario quite frequent in the assembly lines of the automotive sector. In 2013, BMW introduced a HRC system in their plant in Spartanburg (SC – United States) to prevent strain injuries that had been caused by the hand-made placement of a layer of protective foil over electronics on an inside door (Knight, 2014). In the summer of 2015, a Volkswagen followed the example within their plant in Wolfsburg (Germany), by adding a robot colleague in their Golf assembly line to provide help to the human operators, relying them of the unergonomic task of screwing a support pendulum on an engine location that has difficult access (Glock, 2016). More recently, in 2017, Audi implemented two HRC production systems in the A4 and A5 models as a part of the company strategy for its plant at Ingolstadt (Germany) to become a smart factory and to reduce quality problems resulting from human errors caused by the difficulty of some tasks (Taner, 2017).

All the mentioned case-studies had one thing in common. Besides resulting in major gains in productivity by reducing the cycle times, and increasing the quality on the finished products, it had also increased the motivation of the human operators who now have easier tasks less exposed to injuries or other health issues, and less pressure, since the critical tasks of the assembly process are performed by the robot colleague.

2.3.2 Safety in HRC implementations

As illustrated in the previous subchapter, HRC is a solution that has been adopted by many companies in the automotive sector has a way to automatize and optimize their processes. Still, for many companies, the major factor in the "go/no go" decision when it comes to add robotic colleagues in human-centred production cells, is the collaborator's safety itself.

As this type of technology has advanced throughout the years, different strategies have been adopted to ensure the safety of the company's human workforce while working in a human-robot collaborative workspace, which can be resumed in the following (Michalos et al., 2015):

- **Crash Safety:** It ensures that a potential collision between a robot and a human could not result in serious consequences for the second one, so the power/force specifications of the first one is limited;
- **Active Safety:** Using proximity or force sensors or vision systems to predict and avoid potential collisions by stopping the operation in process immediately.
- **Adaptive Safety:** To prevent constant production breakdowns caused by stopping the robot's operation's the hardware of HRC equipment's is constantly intervened, to adapt it to the current conditions and prevent accidents.

While designing the safety considerations for a HRC workstation, it is important to know and the type of interaction that the human performs with the robot, since the strategy and the measures implemented differ from each other. There are three types of interaction modes that can be highlighted (SICK Sensor Intelligence, 2018):

- **Collaboration:** The robot works in mobile work station and performs pick and place tasks and present the pieces to the human operator in an ergonomic position. The might risks associated with are collisions, shearing or crushing and might be avoided by creating special areas equipped with scanners, that in case their violated the robot limits the force or speed exerted or stops completely.

Figure 6 Collaboration mode between Human and Robot (Source: SICK Sensor Intelligence, 2018)

- **Cooperation:** In this situation, is the human who presents pre-assembled pieces for the robot to finish the task. The robot grabs the piece and assemble it in a specific zone. Once again, there are collision risks and a scanner area specification that reduces the robot speed once it detects the human presence are the most suitable risk reduction measures, so as the fencing of the robot specific working area.

Figure 7 Cooperation mode between Human and Robot (Source: SICK Sensor Intelligence, 2018)

- **Coexistence:** In this example, the robot picks the piece from the conveyor and place it on a rotative table where the human collaborator works on the opposite side. At this example, the risks only are associated with the rotative table, and therefore could be minimized by a light curtain that detects the entrance of the collaborator in the work cell and stops the rotating motion of the table.

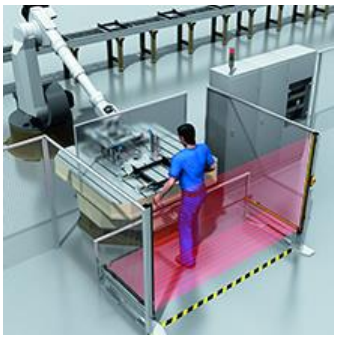

Figure 8 Coexistence between Human and Robot (Source: SICK Sensor Intelligence, 2018)

From the previously mentioned examples, it is possible to notice the implementation of sensors along the work cell that create specific zones to control the robot configuration. That's why Michalos *et al.* (2015) proposes three distinct levels of safety zones to be considered, while designing the safety features of a HRC cell:

I. **Safe Area:** While other collaborators are in this area, the robot can perform its tasks in full speed, and the humans can move safely.
II. **Warning Area:** If the sensors or the vision system detects the entrance of a collaborator in this area, a visual or a sound signal should be emitted to warn the collaborator, and the robot should immediately slow down its speed.
III. **Unsafe Area:** Once the collaborator enters this area, the robot immediately stops its operations.

Besides the strategies and approaches proposed by different authors, there are European and International directives and standards that need to be full filled**.** According to ISO 10218 (ISO International Organization for Standarization, 2006) and ISO/TR 15066 (Matthias, 2015), collaborative operations should visually signalized and can be divided into 4 categories, being the last one regarding power and force divided into two subcategories: (Ruas, 2017):

- **Safety-guided monitored step:** The robot must stop and stand still while the operator is in the workspace and may resume its automatically operations once the operator leaves.
- **Hand Guiding:** This kind of equipment needs to have an emergency stop button and an enable device. The human-robot interface should be located near

the robot, allowing the human to control it within the workspace. Throughout the operations, the robot speed should be monitored in a safety certified way.

- **Speed and position monitoring:** The robot should adjust its movement parameters according to the distance to the human collaborator;
- **Power and force limiting by inherent design:** The limitation functions on the power/force of the robots should respect the standards, so, if the robot exceeds them, it will stop.
- **Power and force limiting by control system:** In ensures that a control function would be used to guarantee that the robot doesn't exceed the power/force limitations.

2.3.3 Safety Considerations Methodology

For the most generality of machines, the ISO 12100-1 standard presents an approach for the design of a safety project. This methodology, presented in Figure 9 is sustained by two main topics: **Risk Assessment and Risk Reduction**.

The first stage is the **Risk Assessment**. It consists in an iterative step that should be performed at every point of a machine life cycle from the beginning to the end, and should be updated whenever new developments or new modifications are applied (Ruiwale, Kadam, Kulkarni, & Jadhao, 2008). To begin with, it should be **specified the usage, spatial and temporal limits** of the machine, followed by the **identification of the existent hazards**. This last step is the most important one, since a risk or a potential hazard that is not identified, is not possible to be reduced, and therefore, not possible to be controlled. To finish the Risk Assessment topic, all the risks and potential dangerous situations highlighted in the previous stage, should quantified, using a **Risk Estimation Methodology,** and finally it is performed a **Risk Evaluation**, to determine if additional risk reduction measures should be taken, or if the whole safety strategy process ends at this point.

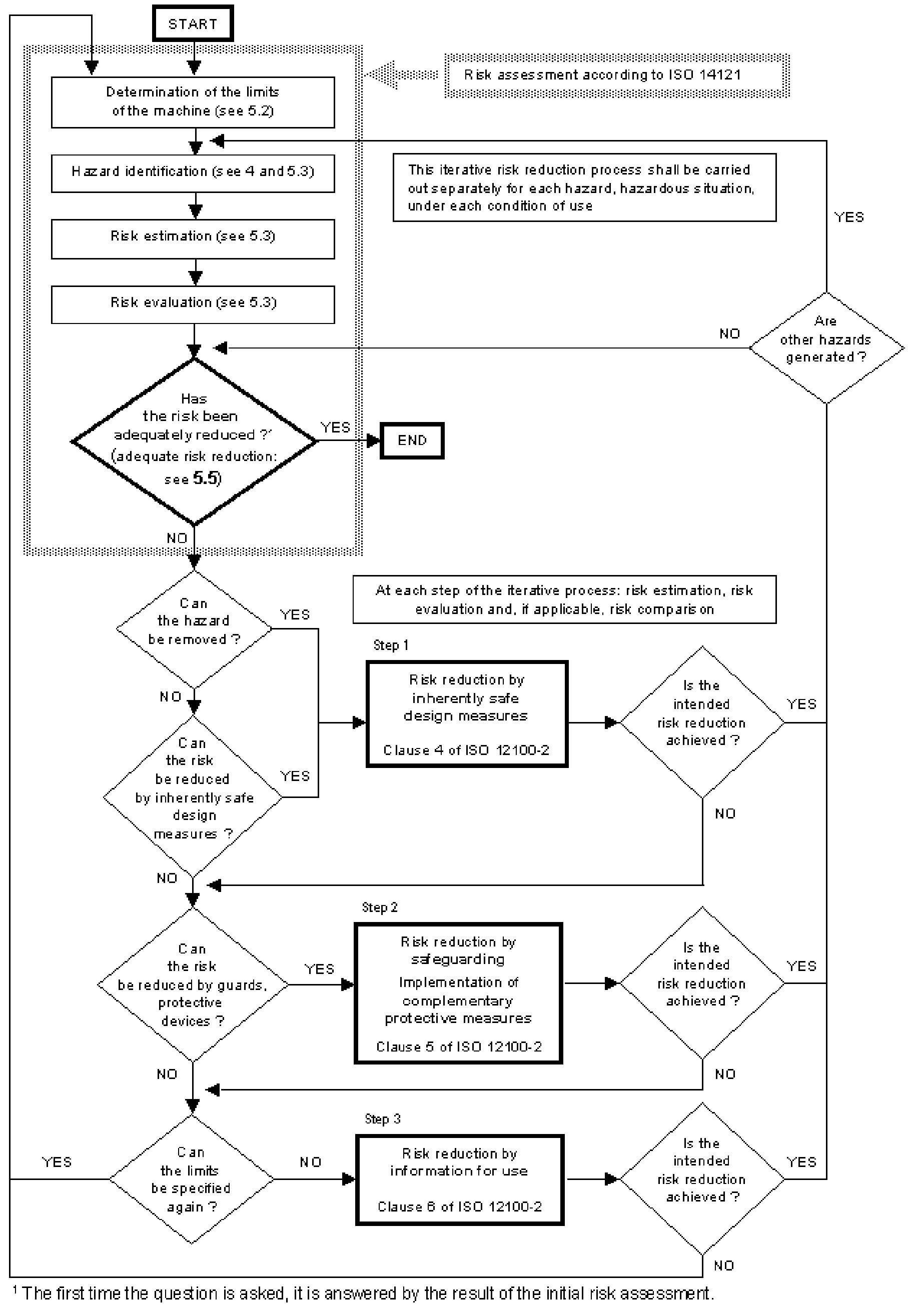

Figure 9 Schematic Representation of a Safety Strategy methodology (Source: ISO 12100-1)

The **Risk Reduction** follows a 3-step methodology. Firstly, all the risk related in the machine design should be removed, in case it is not possible, reduced. In case of the residual risks continue to be too critical to be ignored, the process moves to the second step, which means, adding or implementing adequate protective devices/measures to reduce them. Last, if there's still exist remaining risks that could not be removed or mitigated by first two steps, these risks should be present and properly visible in the machine utilization information.

It is important to mention that the whole safety strategy process is an iterative process, that should be constantly reviewed every time a new risk reduction measure is implemented, to check if the targeted risk has been removed/reduced, or if this new measure originated new risks to be evaluated and removed.

2.4 Simulation

Like most of Industry 4.0 technologies, Industrial Simulation is not a new topic, still it has gain a new importance, at the spotlight of the forth industrial revolution. The current trend for decentralization and globalization of the manufacturing requires real-time information between all the stages of the value chain and the product and processes life cycle, and Industrial Simulation could have an important role on it, has it could leverage real time data to model the current physical scenario with the digital world, being able to include machines, humans and products. (Rüßmann et al., 2015)

To analyse and find improvement points into all this complex systems and flows can turn into a complex process, that would cost time and resources for an organization, while using Simulation, would easier the development and testing of new operations or resource policies or system conceptions so it will meet the desired outcomes, before fully implemented, or simply gathering knowledge and information out of a system, without disturbing it (Pegden, Shannon, & Sadowski, 1995).

2.4.1 Evolution of Simulation

Like mentioned before, simulation is not a recent concept, as many authors consider that it has been originated by the work of the Comte de Buffon, who proposed a Monte-Carlo method-like, many years before the era of computers and its consequent evolution. Still, it was only in the 60's that the first use of Simulation for industrial purposes was recorded, and until today, the study of Simulation had evolved, as it illustrated by Figure 10, to a state where is now possible to fully model plants, workstations, logistic flows, etc… in 3-D and with the resource of high development graphics (Mourtzis, Doukas, & Bernidaki, 2014).

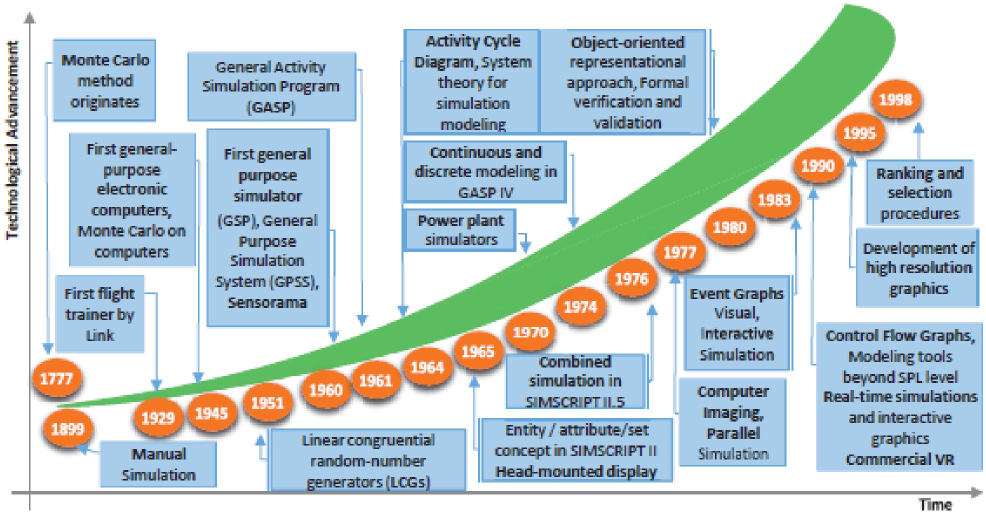

Figure 10 Historical evolution of Simulation (Source: Mourtzis, Doukas, & Bernidaki, 2014)

Throughout the years, Simulation Modelling has developed a great interest, especially in the automotive industry area, which presents several specific opportunities to be approached. Due to the high competition that exists, it is very important to find new ways to reduce the costs and the production lead time. Therefore, there has been a great effort, in the last decade to better design and manage each facility individuality, still, for this objective to be met, the flow of products through and between the production units should be modelled (Pierreval, Bruniaux, & Caux, 2007).

Nowadays, and with the advent of Industry 4.0, Simulation became the focus in many objects of study, for multiple purposes, and therefore, has many definitions, still, the most prominent ones are that **"Simulation modelling is the process of creating and experimenting with a computerized mathematical model of a physical system"** (Chung, 2004) and **"Simulation is the imitation of real world-processes over time. It involves the generation of an artificial history of the system and the respective observation to draw inferences concerning operating characteristics of the real system that is represented"** (Banks, Carson, & Nelson, 2000).

2.4.2 Categories of Simulation Models

A Simulation model can be categorized based on three dimensions: **time, randomness and data organization**. If the simulation depends on time, it can either be **static** or **dynamic**, which means, respectively, the model is timeindependent or if evolves as the time goes by. When it comes to randomness, the model could be **deterministic**, the repetition of the same simulation will result in the same output, or **stochastic,** running the same simulation model different times would produce different results. Finally, for the data organization dimension, it could a **be grid-based** model, which means that the data is associated with a specific discrete cell location in a grid and updates take place to each cell according to its previous state or a **mesh-free** model, which relates with data of individual particles and updates look at each pair of particles (Mourtzis et al., 2014).

Focusing now on the dynamic models, it is possible again to subcategorize the simulation models according to focus of its study into **Discrete** and **Continuous Simulation Models.** The continuous simulation models are often used to reflect situations where the time variable is continuous and to model macroscopic environments, still it can be very hard to model, since it requires a lot of programming efforts. Therefore, most of published works are based on a discrete event world view, which means that changes occur at discrete points in time. These studies, aim to analyse and approach problems such as the overload of production units, the behaviour of inventories and possible shortages, or the known bull-whip effect, working as well as decision support tools for allocation strategies for both human and technological resources as to new investments across the value chain (Pierreval et al., 2007). In Classical Manufacturing, discrete models are used to model the flows of individual products through a set of production resources (machines, operators, logistic transportations, etc…) and the respective waiting queues, while from a Supply Chain perspective, it could model the flow of production orders as batches of products, moving from an unit to another, waiting in inventories, before be transported by a logistic transport (Lee, et al 2002).

2.4.3 Stages of a Simulation Study

To best conduct a simulation study, Persson & Olhager (2002) proposed a 9-step methodology sustained by nine separated activities, which should be performed, before the simulation study is complete:

1. **Project Planning:** Estimation of the timespan of the project and definition of the first set of experiments;
2. **Conceptual Modelling:** The part of the system that is being study should be described by a simple flowchart or a text document to reflect the system logic and retrieve the necessary data for the simulation modelling;
3. **Conceptual Modelling Validation:** The conceptual model is evaluated and corrected if necessary;
4. **Modelling:** The conceptual model is transformed into a computer-based model, using a simulation language or a simulation software package (e.g. Arena, Simio, etc…)
5. **Verification:** Aims at testing the computer-based model against the conceptual model and correct if necessary;
6. **Validation:** Aims at testing the computer-based model against the real system itself and correct if necessary;
7. **Sensivity Analysis:** The effect of varying inputs on the output data;
8. **Experimentation and Output Data Analysis:** The previously defined experiments are run, and the output data is collected and analysed, and if necessary, some new experiments could be run and the step repeated.
9. **Implementation:** The analysed output is used to recommend some decision or to help in an implementation.

It is important to mention that verification and validation are vital activities to achieve an effective and realistic simulation, since if some errors are not detected, the whole decision process that could result from the analysis of the model, might be put into question (Persson & Olhager, 2002).

There are three main types of simulation modelling errors. The first one, error type I, occurs when it is stated that a valid simulation model is invalid and model's output is rejected, while the second one, type II, is quite the opposite, which means it happens when an invalid model is considered as a valid one. Finally, type III, is when the simulation model is addressing the wrong problem (Balci, 1998). Therefore, to avoid these errors, the first stage of the problem, the Project Planning, should be clear enough, to not induce misunderstanding across the rest of the process.

2.4.4 About Simio™

Further in this work, it will be used the software package **Simio™** which stands for **Sim**ulation modelling framework based on **i**ntelligent **o**bjects (Pegden & Sturrock, 2010). Compared to other simulation software packages such as Arena or Anylogic, Simio is a new modelling framework which bases on the principles of object-oriented modelling.

According to Pegden & Sturrock (2010), compared to other classical simulation software packages, Simio, offers a batch of unique features such as:

- A graphical modelling framework without requiring programming skills to add new objects to the system;
- A 3-D supported animation that is integrated in the modelling process that easy the process of animating the model, for it to look more realistic;
- The process modelling features that allow objects with complex behaviour to support many different application areas;
- The framework supports multiple modelling paradigms like both discrete and continuous systems;
- Provides specialized features to directly support finite capacity scheduling that leverage the general modelling capabilities of Simio.

An application of this software on real-life has been developed by the Nissan Motor Iberica SA managers in Barcelona, Spain, which had been using Simio for discrete-event simulation aid since 2015. The outcomes, have been the optimization of the NV200 van production lines at the plant, by using Simulation, to determine the most efficient layout of each assembly line. According to the project manager, this software was selected, due to its ability to help plant managers meet three production challenges: Monitoring diverse and convergent assembly lines that move at different speeds; determining the exact number of vehicle carriers required to meet the plant's projected throughput and validating that product mixes are always correct. This software happened to complement Nissan's engineering tools, has its engineers are now able to study current and planned assembly lines, preventing any design or performance problems (Camillo, 2018).

Chapter 3: Case Study

3.1 The company: A description of Group Simoldes and Plastaze

3.1.1 Simoldes Group – Plastic Division

Simoldes Group is a family business, with headquarters in Oliveira de Azeméis, a city located within Aveiro district, in Portugal, which dedicates to the production of moulds and plastic injected components. Simoldes Group was founded in 1959, ignited by the creation of Simoldes Aços, in a building located in Oliveira de Azeméis city center. In Simoldes genesis were 3 partners: Mr. Manuel Carreira, owner of 50% of the company, Mr. Santos Godinho and Mr. Nélson Lenho, with 25% each. In their curriculum, these men had accumulated experience at an operational level in Moldoplástico, a locksmith company, in which Manuel Carreira had also been a partner until he left. On 1965, Mr. António Rodrigues, grandson of Manuel Carreira, joined this society, and during the 80's, became the only owner of Simoldes, alongside with his family: Mrs. Maria Aldina Valente, his wife, and his son, Mr. Rui Paulo Rodrigues (Rodrigues, 2005; Tavares, 2012).

In the beginning, Simoldes Aços had entered in the mould production market for domestic products such as toys and household appliances, but during the 70's, they start producing moulds for plastic injection, mainly within the automotive area, which quickly became one of the company's main sources of sales revenue. In 1981, it is due to the combination of this new scenario, the growth of the plastic injection industry and António Rodrigues foresight vision, that Simoldes Plásticos (SP) is born. At the new factory, dedicated to the injection of plastic components, António Rodrigues took advantage of the synergy that resulted between the production of moulds, already done by Simoldes Aços, and the supply of plastic injected components (Pais, 2008).

After the 90's, Simoldes Group growth rate had substantially increase, boosted by the investments made in the productive capacity in the mould production and plastic injection in plants both in Portugal and abroad (Lourenço & Sopas, 2003). In the Plastic Division, Inplas was the first new plant to be built (after SP), in 1995, and was succeeded by Plastaze in 1997, both in Oliveira de Azeméis. 1998 marks the year that the Plastic Division expands itself abroad, by opening Simoldes Plásticos Indústria, in

Brazil and Simoldes Plásticos France (SPF). Until today, Simoldes has been a company with an international mindset looking at no borders when it comes to expanding their business further, building another plant in Brazil in 1999, Simoldes Plásticos Brazil, which was followed by Simoldes Plásticos Polska (Poland) in 2004 and Simoldes Plásticos Czech (Czech Republic) in 2015 (Grupo Simoldes, 2017), with the prospect of opening soon another plant in Morocco (Fall, 2016).Besides the plants, Simoldes Plastic Division also has technical/commercial sites in Spain, France and Germany.

3.1.2 Plastaze

Plastaze – Plásticos de Azeméis S.A. is a company, founded in 1997, that belongs to Simoldes Group – Plastic Division and it is located in Cucujães, part of Oliveira de Azeméis Council. Like most of the SP's plants, Plastaze focus their activities in the thermoplastics injections, and the main products that it sells are components for the Automotive Industry, bottle cranes, child's safety seats and gas cannisters.

Figure 11 Plastaze plant outside view (Source: Grupo Simoldes, 2017)

Plastaze has between their main clients, major OEM's such as General Motors, PSA Peugeot Citröen, Volkswagen or Mitsubishi, and in 2017 had a sales value of 36 million euros.

Its production stands on a 10.000m^2 infrastructure equipped with 55 injection machines between a range of 80 to 1700 tons, that inject components from around 400 different moulds. In its human workforce, Plastaze counts with over 580 collaborators that work in a three-rotative shifts system.

Following a strategy of continuous improvement, Plastaze presents as key ingredients to its success the quality of their products and the overall satisfaction of both its clients and collaborators.

3.2 ScalABLE 4.0 Project

3.2.1 Contextualization

On the today's scenario, SP division factories are currently facing a high production rate when it comes to the inject plastic components, and the fact that the automotive sector are SP's main customers, means that producing these components, implies having to deal with a wide range of products with different production complexity levels, with variable lot sizes.

The production process of these plastic components can be divided in two main sub processes: **plastic injection and post plastic injection**. Currently, the **injection process** is already highly automatized due the utilization of peripheric robots that are responsible for taking the plastic pieces out of the injection machines, removing the plastic excess, checking if the produced piece geometry is according to the parameters, and finally place them on a conveyor.

When it comes to the **post injection processes,** there are several tasks regarding assembly and packing with different complexity levels, depending on the product being produced in that respective injection line. There are products which doesn't require any specific packing **(bulk packing),** and therefore, the packing is done through a box placed at the end of the conveyor and there is no need for a human operator, some which need a a **palletized packing** with specific piece positions and if necessary some **simple assembly tasks**, and others, who due to its complexity, need a series of multiple assembly operations, and therefore are transported to dedicated assembly lines, situated on other area of the plant. Before packaging, such tasks might include mechanical assemblies, screw driving operations or quality checking. Still, the lack of flexibility in these post injection processes, which shows a low level of automatization, doesn't allow the traditional robotic solutions to adapt no just to the complexity of the production tasks but to the production demand as well.

Figure 12 Example of a palletized packing line

Figure 13 Example of a simple assembly performed by a human operator next to the injection machine

The preliminary solution found to face this problem of answering different complexity levels coming from a wide range of products with dynamic needs was to, on purpose, keep the automatization level in the post injection processes low, and therefore to hire temporary workers with unattractive contracts, resulting in integration costs associated with a low commitment level for low-value tasks to be performed by human operators.

It is in this context, that Simoldes Plásticos decided to join **ScalABLE 4.0** (Scalable Automation for flexible production systems – ScalABLE 4.0), a project financed by the European program H2020 (EU.2.1.1. – "Industrial Leadership – Leadership in enabling and industrial technologies – Information and Communication Technologies (ICT)"), inserted in the European Union PPP "Factories of the Future". The project coordinated by INESC TEC, counts joins both academia and industry within its partners, having on board, the Aalborg Universitet (Denmark), the Fraunhofer Institute (Germany), Sarkkis Robotics (Portugal), Critical Manufacturing (Portugal), Peugeot Citroen Automobiles – PSA (France) and Simoldes Plásticos (Portugal).
The general goal of this project is the development and demonstration of an OSPS – Open Scalable Production System framework that could be efficiently and effectively used to visualize, virtualize, build, control and optimize a production line. This project also plans to respond the high demand of manufacturing companies, especially in the automotive sector, to have efficient tools that allow to optimize the organization of their production lines "on-the-fly".

To achieve these general goals, the project will be sustained by some Industry 4.0 related technologies such as the development of a system of human-robot collaboration, and advanced plant model through simulation, advanced decision support technologies and advanced "network" interface and "plug n' produce" technologies. Each of the main functional areas called Work Packages of the project were divided by the main partners of project based on their areas of expertise but in a symbiotic environment that stimulates the sharing of information and knowledge that allows each of the entities involved to achieve their goals.

SP was responsible, alongside with PSA, with the Work Package related with the application-case Definition and as end-users of the project, and has the responsibility as well, to provide useful information to the remaining partners whenever it is necessary.

3.2.2 Project Goals

In the SP context, the main outcome of this project, was to create and develop the first multi-product production line within the group's factories, capable of efficiently dealing with variations in the exigence level, using the adjustable robotic solutions developed by Scalable 4.0. Besides that, the Scalable robots should be able to perform complex assembly tasks, promoting the interchangeable tasks paradigm, as well as the collaboration between operators and the robotic systems.

These robotic systems should not just have the capacity to easy the human operator's tasks by lighten them of repetitive tasks that adds low value to the finished product, but also to count with them to collaborate with more complex operations.

It is also, the SP's expectation that this project could also be the first stage for many other developments and improvements in other functionals areas of the organization, specially within logistics and production engineering.

Still, like it was mentioned in the Introduction of this work, the project is expected to last three years, and since this work would only cover the first year of the project, it will mainly be focus on the preliminary work needed before the physical implementation. The goals of this project, were to come up with a proposed, validated and effective solution for the new scenario to be implemented in the affected workstations, that should meet the safety requirements as well as to achieve the application cases KPI's.

3.2.3 Methodology

To meet the previously mentioned goals, the adopted methodology was divided into three major steps. The first one, was to clearly define which areas should be selected for the implementation, to best reflect the potentialities of the project for the organization while avoiding high costs inherited to it (e.g. layout changes), as well as to collect all the necessary data for the upcoming steps. The second step, after selecting and defining the application cases, was to come up with a group of considerations that should guarantee the safety of the employees in the HRC implementation, as well as to make sure that the process keeps efficient and productive. Last, but not least, considering the data collected from the selected workstations, the safety considerations, and the robotic information provided by the project partners, create a simulation model that should be able to reflect how the Scalable scenario would perform, so the company should know in advantage, which decisions should take, before physically implement the new system in the plant.

3.3 Definition and specification of the application cases

The first stage of the work was to define the application cases to be selected as the focus of project. This way, based on the bigger context, it was decided that Scalable 4.0 should tackle two different application cases related with the two categories of post-injection processing of products, since the injection process is already highly automatized, which means, simple and complex products.

3.3.1 Application case Definitions

a) **Simple Products: Multi-product line**

Like it was mentioned in the contextualization subchapter, after a piece is placed in a conveyor, depending on its characteristics, it might need some specific assembly or packing operations or none. Within the packing operations, the piece might also need a plastic bag, so it's not damage during transportation. These operations are performed by human operators who are standing near the injection machines, and due to the average one-minute injection cycles, they could be dedicated to one or two injection machines, according to demand variability and task complexity.

The main problem of this application case, is that human operators are performing highly repetitive, unergonomic and low-value adding tasks. Still, to automatize the current post-injection processes for simple products, with the current injection machines layout, would require an immense investment in robotic equipment in the future, since there are more than 40 injection machines per plant in SP division, and besides, due to the long injection cycle time, variability in production demand, and to low complexity of the operation, the usage rate for each stationary robot would be unsatisfactory low.

To tackle these drawbacks, Scalable 4.0 will consider different layout solutions for a multi-product production line, where humans, robots and the automation equipment could be more efficient in the post. Implementing such configuration as this would bring two main advantages: Centralizing all the post injection processing components to a single area of the plant floor, shared by both humans and collaborative optimizing the production area, and concentrate all the internal logistic effort in a single region, making it more efficient. The result would be a flexible and automated work force composed by humans and collaborative robots, and a possible increment on the number of injection machines that could be now fitted in the plant floor, and a less necessity for internal logistic vehicles would diminish the number of constraints currently existing.

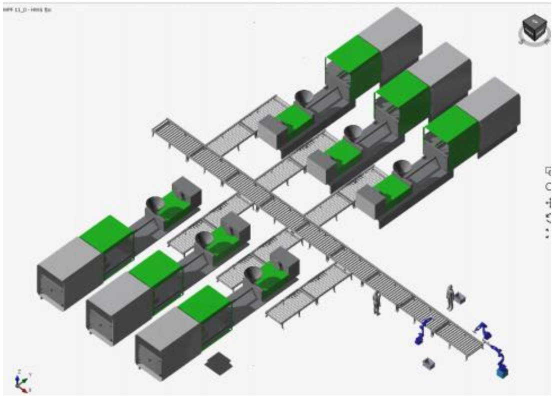

Figure 14 Proposed layout for the Scalable 4.0 multi-product production line

b) **Complex Products: The car door handle assembly lines**

As previously seen, for products that requires a more complex set of assembly tasks, there are dedicated assembly lines, placed in another location of the plant. This happens due to the fact that this kind of tasks requires more space to be perfomed and have a cycle time bigger than the injection cycle, which since the same tasks doesn't allowed to be paused and resumed, would result in an efficiency in the production.

One example of this complex products are the car door handles for the automotive industry. Interior car door handles are a complex product composed by different components that complement the plastic part molded, like the handle, the components for the spring mechanism, as other optional components depending on the car model (e.g. LED light, chromed handle, etc…). SP produces car door handles for diverse automotive brands, with different car models, which represents a great product variation just for the car door handles, so the customer preferences could be met.

Another issue that motivated the selection of this application case was the fact that this kind of assembly tasks had been pointed out as the origin of many arms and hand's related injuries within the human collaborators. This happens due to the force exerced in the pieces during assembly and the constant contact with the auxiliary equipment that checks the quality of the piece.

Therefore based on each product demand and on SP necessities, there were three projects selected for this application case: the Seat Ibiza, the Volkswagen Polo, and the Volkswagen T-ROC.

Unlike the first application case, for this one, due to the complexity of tasks, and the exact tasks that the Scalable robot should perform, there isn't any layout proposal for the new scenario, and that should be a situation to be developed along the project, once the first physical tests are performed. Still, it is SP intention that Scalable 4.0 could provide a human-robot collaboration solution that could leverage the collaborators tasks, which would result, besides less health related abstentism, in a more motivated workforce. The other expected results, are a reduction on the cycle time of the process, and the increment on the quality of finished product, by removing the human error factor.

3.3.2 Environment selection

To choose the right environment for this project to be implemented, the principal criteria was to choose an application case that could both produce significant results for the company in a long-term, but also, not to create big production restraints in the plant, which would result in major costs. Therefore, the selected locations were two work stations in Plastaze, for each of the application cases. For the multi-product line, it was selected the Module 3, since it was composed by low-dimension machines, and easier to change the layout if necessary when compared to bigger machines and more adaptable for a multi-product line. For the complex assembly line, were selected three lines for car door handles assembly lines, since where the assembly lines in Plastaze, that would result in more benefits, if the productivity were increased through automatization.

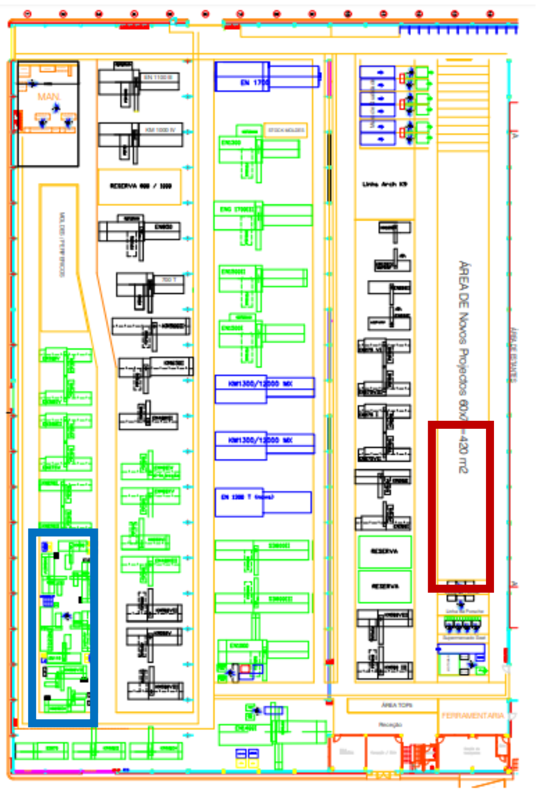

Figure 15 Plastaze layout, with the application cases location in blue (multi-product line) and red (complex assembly)

3.3.3 Application cases specification

Once the application cases were defined, and the environment selected, the next step was to specify each application case to the detail, so the necessary information could be easily visualized and accessible. This meant detailing all the tasks necessary to produce one piece in each application case, and its order across the flow. The goal of this stage, was to further on, create a simulation model for the proposed scenario, and to select the tasks that could be performed by the Scalable robot.

a) **Simple Products: Multi-product line**

For the first application case the first task was, due to the great variability of different products, create a generic BPMN model for all the post-injection processes that are performed next to the injection machines.

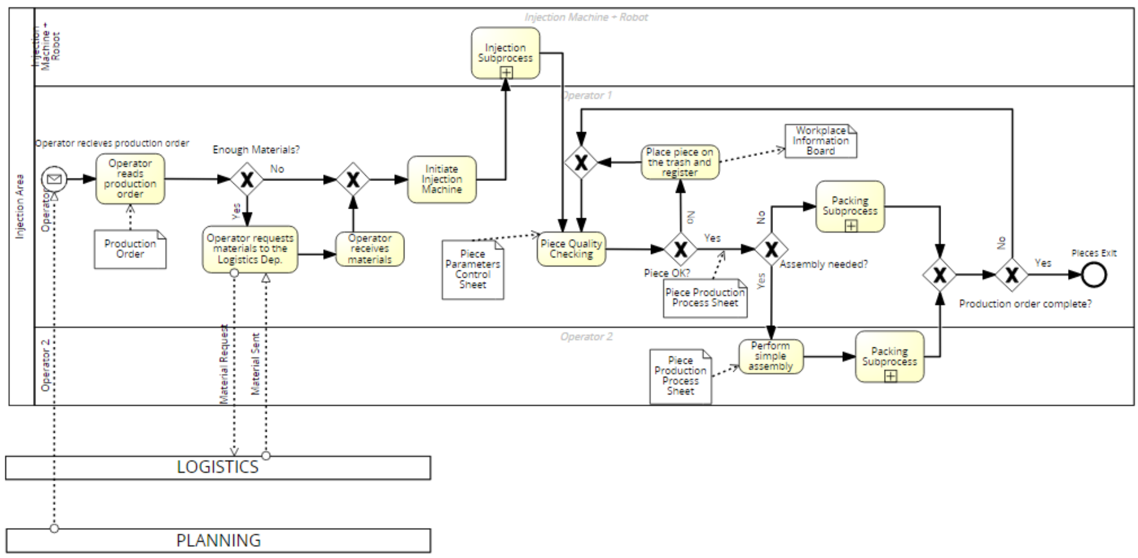

Figure 16 BPMN Model of the Post-Injection Processes

In Figure 16, it is important to mention that, the Packing Sub process can be deployed into two types of operations depending on the mould in production. In case of bulk packing, the operator only checks the piece quality time to time, and let the conveyor transport them directly to the container, replacing it once it is full. For the palletized, the operator needs to perform more complex, since the pieces must be packed in a defined position.

Afterwards, it was needed to stablish a list of products that would be selected to be part of project. This task was needed, since it was important for the other partners of the project to know the kind of parts that the robot should work with, and to be aware of the type of packing that each part needs and if a simple assembly is needed or not.

The selected parts, all currently produced at the Module 3, presented on Table 1, were chosen, based on the criteria of the reference project length, and if the level of the product share on the total level of orders within the factory is significant. For each product, it was registered if the part needed a bulk or palletized packing and if there was a need for a simply assembly or not.

Table 1 Moulds selected for the Multi-Product Line Case-Study

Machine	Mould	Packing Type	Assembly Needed?
KM 80-I	MO. 7247	In Bulk	No
	MO.7249	In Bulk	No
	MO. 8536	In Bulk	No
	MO. 7833	In Bulk	No
	MO. 8112	In Bulk	No
	MO.8220	In Bulk	No
	MO. 8487	In Bulk	No
	MO. 8535	In Bulk	No
EN 110-I	MO. 7480	Palletized	No
	MO. 7503	In Bulk	No
	MO. 8238	In Bulk	No
	MO. 8491	In Bulk	No
	MO. 8534	In Bulk	No
KM 200-IV	MO. 6913	Palletized	Yes
	MO. 7017	In Bulk	No
	MO. 8265	Palletized	Yes
	MO. 8428	Palletized	No
	MO. 8463	Palletized	No
KM 200-V	MO. 7029	Palletized	No
	MO. 7103	In Bulk	No
	MO. 6568	Palletized	No
	MO. 7640	Palletized	Yes
	MO. 7717	In Bulk	No
	MO. 7819	In Bulk	No
	MO. 8080	Palletized	No
KM 200-III	MO. 7534	In Bulk	No
	MO. 7847	Palletized	No
	MO. 8600	In Bulk	No
	MO. 8611	In Bulk	No
	MO.8816	Palletized	No
EN 225-II	MO. 6830	Palletized	No
	MO. 7793	In Bulk	No
	MO. 8537	Palletized	No

Once this information was collected, the next decision was the role of the Scalable robot in the new multi-product, by other words, the specific tasks that it should perform. From Table 1, it is possible to retrieve that just a few moulds need a simple assembly before packing. This task, due the complexity of the inherent operations, must be performed only by a human operator.

Another important information that is retrieved from Table 1, is that the distribution between palletized and in bulk packing pieces is almost 50-50. The Bulk packing is already automized, since the piece only flows through the conveyor straight to the container, doesn't needing any additional task from both human or robot. This means that the robot would create a bigger impact in the palletized packing, which is composed by repetitive a non-value adding operations that currently requires a dedicated operator to perform them.

For the Scalable robot to perform the palletization operations, there were two possible approaches. The first was the robot to palletize each piece, according to the positions showed in the current Packing Sheets. The other one, was to change the Packing paradigm, by using blisters to pack the pieces that need to be palletized, which would easier the robot task, since it would be already programmed to deliver the piece in that specific location and wouldn't need to perform different movements to place the piece in the container. The best approach should be selected according to one who best full fills the project goals, which means, the one who could best represent a better productivity, better quality and lesser costs.

b) Complex Products: The car door handle assembly lines

Unlike the previous case study, the car door handle assembly process is quite simple, since the current situation resembles a traditional assembly line, the product enters the line, the human operators perform a group of assembly operations and it is packed. Here the main is to increase the productivity of the line, by relying the operators of repetitive tasks, that sometimes results in quality issues. Still, there are tasks, that due to the mobility and flexibility of the human arms and hands, only the operator can perform. Therefore, the main task at specifying the case study was to group all the required tasks and analyse how it could be regrouped to divide the workload between robots and humans.

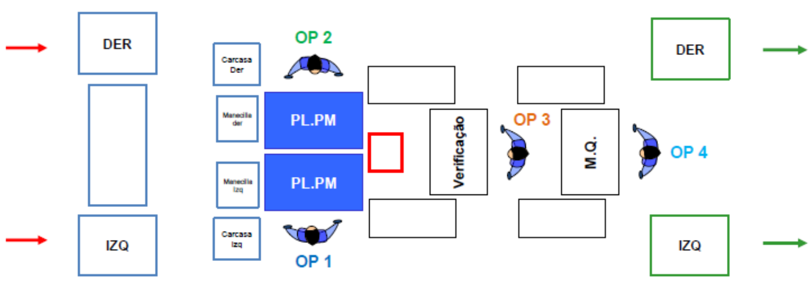

Figure 17 Example of a generic assembly line layout

Generally, the tasks can be subdivided into the following groups: Inspection, Puffer, Spring, Handle, Rod and Packing. The inspection relates with the visual inspection of the handle quality and it is performed by the operator. The Puffer operation is composed by the insertion of a small plastic component into the plastic part, avoiding doing any damage to the handle when closing it. The spring assembly is the most precise assembly operation, due to the reduced assembly gap. The handle is assembled to the plastic part through the insertion of a rod. Due to the force required to insert the rod into the handle and the plastic component, it exists an auxiliary equipment that aids the operator. Finally, for the Packing operation the finished door handles are packed in palletized fashion in specific containers.

Although the operations are mostly transversal to all the car models, each model might have particularities that still need be considered. An example, is the fact that the in Seat Ibiza assembly line, the assembly of the handle is the last operation to be performed while on the Volkswagen models, it is the basis of the assembly whole process.

Based on each task complexity, after consulting with the Process Engineering team and the robotic development partners within the Scalable 4.0 project, it was drawn a table for each of models in study. In each table, presented in Appendix I of this document, were described every task associated with the respective assembly operation and whether it could be performed by a human operator, a robot or the auxiliary equipment. In some cases, it was not possible to predict if the robot will be able to perform the described tasks, and therefore, an interrogation mark was used.

3.4 Safety considerations for Implementing HRC in Plastaze

After the case-studies were selected, the next step of the work was one of the most important in the whole HRC implementation. As one of the partners designated as end-users of the project Scalable 4.0, it was SP responsibility to perform a Safety Analysis within the selected workspaces, to better understand what might be needed to design and implement in the new workplace, so it could reduce or overcome both actual and potential safety of the case studies.

Before igniting the methodology proposed by ISO 12100-1, the first step to be taken was to gather the Safety and Health Section of Plastaze and SP group to listen and register all the important inputs they might have to add for the HRC implementation proposal. According to them, like previously mentioned, the HRC implementation could bring many benefits for the human collaborators health, by relieving them from unergonomic tasks that usually result in upper limbs injuries and more health-related absenteeism. Still, it was mentioned that one of the main concerns related with it, might be the education and information provided for the collaborators, which could jeopardy the whole implementation, and bring additional problems to the company if they misunderstood or not be aware of the whole purpose of this implementation and the new way to perform everyday tasks that it would bring.

To also have inputs on the robotic side and on the technical risks and potential solutions that could be study for the HRC implementation in Plastaze, Sarkkis Robotics, one of the partners of the project, was consulted and visited the plant. At this stage, many risks and the respective potential solutions were pointed up, most of them regarding the best way of having both robots and humans in the same workplace, but trying to avoid the direct contact between them, since it would result in the stopping of the robot, and a whole production breakdown.

As most of the stakeholders that could provide precious inputs to the Safety Analysis of the proposed HRC implementation solution, all the knowledge gathered was analysed, and a General Risk Assessment was made, combining both actual and potential risks. After each risk was identified, it was classified the probability of occurrence as low, average or high, and the severity of the consequences as Slightly Serious, Serious, or Extremely Serious. Based on the classifications of the probability and the consequences, the Risk Evaluation was made, being classified through a 5-level scale from the lowest level Trivial to the highest one, Intolerable. The General Risk Assessment is presented in Table 2:

Considering the fact, the risks identified for in the two case studies were similar, it was decided to create one general risk assessment for both. Reminding the importance of this stage for the whole implementation, some generic risks inherited to a HRC were also retrieved for external sources. (Omron Industrial Automotion, 2018)

Table 2 HRC Implementation General Risk Assessment

GENERAL RISK ASSESSMENT											
Identified Risk	Probability			Consequences			Risk Value				
	L	A	H	SS	S	ES	T	TO	MO	I	IN
Repetitive body movements for more than one hour	•			•			•				
Messy workplaces, garbage not removed, spillage not cleaned		•		•				•			
Impacts/compressions in superior limbs (hand/arm)	•				•				•		
Impacts/compressions in inferior limbs (feet/legs)	•				•				•		
Hair, clothes, jewellery might get caught by robot in movement	•				•				•		
Unexpected or uncontrolled robot movements	•				•				•		
Exposure to sharp edges might result in cuts or abrasions	•				•				•		
Body parts get in contact with sharped, hot or under tension components during test,	•				•				•		
Projection/ejection of particles, components, pieces or fluids	•				•				•		
Injuries caused by the impact with dislodged part from the end-of-arm-tooling	•				•				•		
Clamping forces on the end-of-arm tooling or fixtures can cause an injury	•				•				•		
Production breakdown caused by getting in contact with the human operator		•			•				•		
Transition between non-collaborative to collaborative workspace misunderstood by the human collaborators		•		•				•			

L – Low, A – Average, H – High, SS – Slightly Serious, S – Serious, ES – Extremely Serious, T – Trivial, TO – Tolerable, MO – Moderate, I – Important, IN - Intolerable

After the Risk Assessment was performed, both the Health and Safety section of SP and Sarkkis were consulted, to develop risk reduction/prevention measures. Like the Risk Assessment process, the methodology adopted was the one proposed in ISO 12100-1.

The first risks to be tackled were the ones who revealed a higher risk value classification, and to better understand them and approach them, they were divided into human or machine behaviour.

For the human behaviour risks, some of them were already been like the ones found on the current scenarios, such as messy workspaces, possible impacts between the limbs and the machine or the risk of elements such as long hair or other jewellery to be caught by moving components. For these problems, since it only depends on the human side, it was not possible to adapt the machine for these circumstances, so the prevention solutions developed concern mainly ensuring that the collaborators follow the existent conduct guidelines, respecting the importance of keeping their workspace clean and organized, using protective equipment and avoiding using necklaces or bracelets that could be easily caught by a moving component and using the hair attached. It was interesting to notice that with the proposed scenario, although there is still a chance of the operator to perform repetitive movements, the probability of it to happen was now lower.

With the HRC proposed scenario, there were other human behaviour risks that came up, mostly regarding to the relationship between him and the new robotic colleague. One of the features of the collaborative robot is the fact that it can stop once it detects the contact with an object strange to the task it is performing, by other words, the human worker. This feature might be a risk elimination solution when it comes to potential impacts between the human and the robot, but it also creates another risk, since it will cause of constant stops, which could cause a production breakdown, resulting in losses for the company.

Therefore, similarly to the examples found in the chapter 2.3, it was proposed the creation of safe, warning, and unsafe areas, delimitated by an area scanner or physical barriers embedded with photoelectrical sensors. This safety system would create awareness for human collaborator for the areas that he should avoid, reducing the probability of the production to stop due to the contact between robot and human.

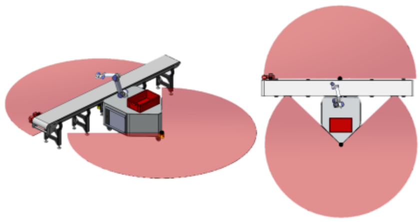

Figure 18 Bird and Top View of the Safety System for the Multi-Product Line Case Study equipped with a laser scanner (Source: Sarkkis Robotics)

This safety system proposal would also answer some risks related with the machine itself, such as the clamping forces of the end-of-arm tooling, since the implementation of the area scanner would allow the robot to work at full speed, if not detecting any human presence in the surroundings. If it does, the robot, would then move immediately to a collaborative mode, in which it would work at a harmless speed rate for its human colleague.

Table 3 Risk Reduction/Prevention Plan

RISK REDUCTION/PREVENTION PLAN		
Risk	Corrective/Preventive Measures	Priority
Repetitive body movements for more than one hour	Allow short timed pauses for relaxing and muscular decompression	Low
Messy workplaces, garbage not removed, spillage not cleaned	Constant cleaning of the workspace and educate the collaborators on keeping it organized	Average
Impacts/compressions in superior limbs (hand/arm)	Use of protective gloves	Average
Impacts/compressions in inferior limbs (feet/legs)	Use of protective shoes	Average
Hair, clothes, jewellery might get caught by components in movement	Mandatory use of attached hair, and prohibition of objects that might get easily stuck such as necklaces, bracelets, etc…	Average
Unexpected or uncontrolled movements	Create safety conditions before initializing the work and specific education and information on the machine's behaviour.	Average
Exposure to sharp edges might result in cuts or abrasions	Use of grippers with round edges, more compliant, softer materials, and wider contact surface areas	Average
Body parts get in contact with sharped, hot or under tension components during test, inspection, maintenance or cleaning	Conditionate the access to the machine to a selected group of people; Create safety conditions before initializing the work and specifically educate and inform the collaborators in the maintenance area.	Average
Projection/ejection of particles, components, pieces or fluids	Use of protective glasses	Average
Injuries caused by the impact with dislodged part from the end-of-arm-tooling	Add reductant mechanisms to detect and further reduce the uncontrolled loss of parts	Average
Clamping forces on the end-of-arm tooling or fixtures can cause an injury	Design different safety areas, that if the robot detects the human proximity in each one or not, it will work at different speed/force rates	Average
Production breakdown caused by getting in contact with the human operator	Conditionate access to the production area; Implementation of physical/photoelectrical barriers that will inform the worker at which point he should not cross	Average
Transition between non-collaborative to collaborative workspace misunderstood by the human collaborators	Inform and educate the collaborators for the changes that a HRC implementation would bring before it is physically implemented	Low

To conclude the safety analysis, the last step was the creation of a risk reduction/prevention plan to be further analysed as the project evolves and to be taken into action before the HRC physical implementation. This plan, illustrated by Table 3, shows all the risks previously identified and mentioned, as others were discussed and individual solutions for each one of them were proposed, so as the priority of each one of them.

3.5 Development of a Simulation Model

Once the application case specification was complete and the safety analysis for the new HRC system done, the next and final stage of this work was to carry a simulation study to predict the potential impact in the current production and to support further decision taking processes that would come up during the project (e.g. layout validation, task allocation, production orders, etc…)

Within Scalable 4.0 partner responsibilities, SP's role in the Simulation was merely as an information partner, and as a collaborator in the simulation study that is still being conducted to both the case studies, and being leaded by INESC-TEC. Therefore, since the project is still on going, it would not possible to present the model with the concrete data from each piece, and its different behaviour across the production line, so as the exact quantified results that are already able to retrieve from the model. Instead, in this chapter it will be explained all the work developed by Simoldes during the Simulation study that would be concluded by a more generic simulation model for the multi-product line, based on the products characteristics (bulk or palletized packing and the need for a simple assembly) developed with the data and the knowledge collected during the internship.

3.5.1 Project Planning

Based on the mentioned case studies description and characteristics, it was decided to build a dynamic discrete and stochastic model. This was justified by the fact that the objects of study were two workspaces exposed to different kinds of variations that affects the time cycle, and therefore, hardly would be represented by a model which would reflect always the same output.

An important task to be performed at this stage, was the definition of the experiments to be ran in the simulation model, and the Key Performance Indicators that should be measured to analyse the quality of a HRC implementation. The initial indicators that SP wanted to study from both case studies were the solution's impact on the productivity of the production line and on its time cycle, and the utilization rate of the implemented robot. Still, after the Safaty Analysis was performed, it was decided that an important experiment that should also be ran in the Simulation model, was the fabric orders and the robot/human task allocation. This experiment was important to be considered since based on the safety analysis described in the previous chapter, the robot could only perform its tasks at full speed if he does not have any humans in the surroundings, and in case it has, it should perform them at a collaborative speed. This way, it was interesting to understand how the multi-product line would behave if the production orders were made to best group the pieces that only need a palletized packing (performed by the robot) and the ones who need a simple assembly (performed by human), so the robot could perform at its maximum speed most of the time.

Also for the multi-product line, the proposed layout by itself would already bring changes to the current production scenario in the plant. Therefore, it was important to understand through the simulation model, if even without the robots, the new layout would imply changes to the productivity of the line.

At this stage of the project, it was decided to not invest time on developing a simulation model for the complex assembly case study, since the proposed concept of the new HRC production cell is still under development by the investigation partners and Simoldes, and still requires further testing before it is modelled.

3.5.2 Conceptual Modelling and Validation

The next step of the simulation study was to develop a conceptual model that would represent the logic of the systems intended to be simulated. It was developed a conceptual model based on both operations flowcharts and textual information for the task sequence, which were respectively validated by Plastaze Process Engineering Team.

For the Multi-product line case study, to model the concept of the proposed implementation, the BPMN model showed in Figure 16 was used as starting point to represent generic post-injection processes for simple products. According to the project characteristics, a new, updated, and simpler model, presented in Figure 19, was created:

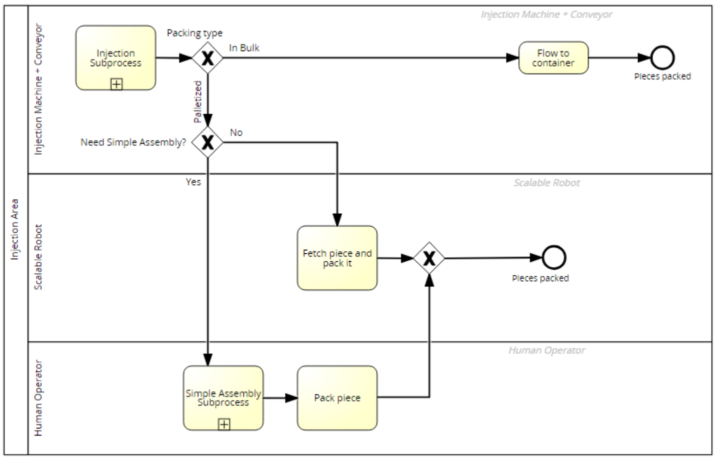

Figure 19 Simplified BPMN model of the scenario to simulate

Although the generic process might look simple, the main difficulty of this case study simulation stood on the huge variety of products that flows throughout the process and the different level of complexity of production that leads to changes in each piece cycle time. Since this type of variations already start on the injection process itself, it was collected all the injection times for each piece and are presented in Appendix IV.

For the rest of the post-injection tasks, since it would cost a lot of time to model all the tasks associated with every piece, when there were many of them which were equal and with similar times, there were selected two to three pieces per machine, to represent the different types of tasks that could be performed, as all the assembly tasks performed by the operator. Those tasks were presented in the Appendix II of this document.

3.5.3 Preliminary Model in Simio™

For the simulation of the modelled scenarios, it was needed to translate them into a computer-based model, with the aid of a simulation package. For this case, Simio™, was the chosen software.

The goal of this stage was to represent how the HRC systems proposed for both HRC systems would behave when compared to the current scenarios, measuring the impact that it would have in the selected KPI's, if the desired expectations are met as other work that still needs to be done.

At this phase, one of the main drawbacks that were presented was the fact that the robots weren't ready yet to perform the necessary tests, to have reliable data on its performance. Therefore, the solution find, was to use the data that the robot suppliers expected for it to correspond once it is implemented, and, specifically for the multi-product line case study, to simulate it, without the robots, just to test the layout change.

To best illustrate the impact that the Scalable project could bring to the new implemented multi-product line, based on the collected data on the workstations, and in the BPMN model of the proposed solution, it was developed a simulation model, shown in Figure 20. The model presented, was developed more to give a qualitative point of view on the proposed solution rather than a quantitively one. This happens, since the concrete data from the robot speed rate is still not available, and the tasks that it would be able to perform or not had not been physically tested yet.

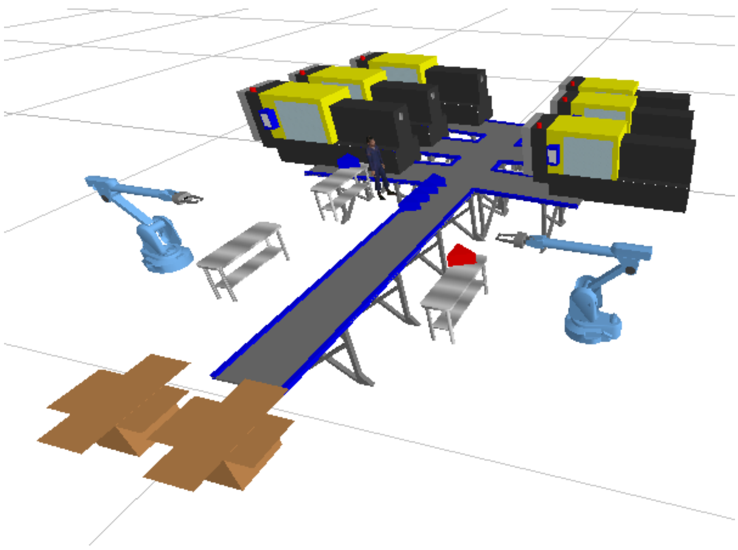

Figure 20 Screenshot of the Multi-Product Line Simulation Model in Simio™

For the model presented in figure 20, it was firstly considered the scenario, where a human operator works at the same time as the collaborative robots, and the last ones are just responsible for the palletized packing of the pieces once they get to them. Besides the speed restriction when working near humans, that was already mentioned previously in this document, the simulation enlightens another drawback that might reduce the robot's usage percentage and the line productivity, which is the bottleneck created for the pieces that need a simple assembly performed by a human operator.

Quickly, is it possible to provide a solution for this problem, by changing the production schedule, by synchronizing the injection machines to mostly produce pieces that only requires a palletized packing instead of simple assembly operations, and afterwards, by mostly producing pieces that requires simple assemblies, and providing another human operator to the line.

The results were an increment in the robot's utility percentage and the proof that is it possible to remove human operators from this cell without affecting its productivity, which would result in cost savings for the company.

3.6 Future Work and Expected Results

After this work is complete, the future passes by the experimentation with the real Scalable robot, which is still being developed by the other project partners. In a few months, SP could start testing the robot within a physical production line in a controlled simulated workspace in INESC-TEC, before fully implementing it in Plastaze plant. Further, are presented the following steps that should be taken for each chapter of this work, and the future results that expected to be retrieved from the project implementation.

3.6.1 Specification of the application cases

During these experimentations, SP should study the behaviour of the robot in the pick and place tasks, within the multi-product line, and test both proposed approaches for the palletized packing (keeping the current palletization steps or adopting blisters). This means, that at the same time, a study on a potential blister investment should be taken, so in case this solution is adopted, a supplier could be selected, and the project keeps flowing without any further delays. To fully visualize both approaches in a more plant-likely scenario, after the tests, a simulation study should be conducted based on the real robot cycle times, to better understand each approach impact.

The principal result that is expected for this case study are the cost savings that results from reducing the number of human collaborators in the workspace by transferring them to more value adding tasks within the plant, such as complex assemblies. Other expected results, sustained by the simulation studies, are the increment of the workspace productivity and the decreasing of the lead time.

Although, it is more difficult to recreate the assembly lines conditions for the car handle case study, the most important step to study in this case, is to test if the robot can perform the selected tasks and the time it needs to perform it. Based on this data, the simulation models should be updated, to test the rentability of the HRC implementation for this case study. Like the multi-product case study, the simulation model that regards the car door handle case, should be updated to include the real robot times.

Also sustained by the simulation model, updated with the real robot times, the expected results should reflect an increment in the productivity and a time cycle reduction compared to the current situation.

3.6.2 Safety Considerations for Implementing HRC in Plastaze

Although the chapter itself already provides clear guidelines on what should be done in the future before implementing a HRC solution within Plastaze plant, it is important to underline that the presented Risk Assessment and Risk Reduction Plans tables should be reviewed after the tests at INESC-TEC. This revision should be done in accordance with ISO 12100-1, since its mandatory every time there is any change or any significant development of the workspace. Physical experiments the robot, could provide more enlighten to other potential risks as well as other risk reduction/prevention measures.

Coming back to the Safety Analysis developed in this document for the proposed HRC workspace, it is crucial for SP to start creating the conditions for this implementation to take place, even if it is scheduled to happen two years from now. To mitigate potential risks when it happens, SP should start to draft a plan, in which should focus the human side, and come up with concrete measures to adapt the plant for this new reality.

Throughout the Risk Reduction/Prevention plan, it should be expected a smooth transition between the traditional production paradigm and the HRC one, with more benefits for the human collaborators, by reducing the number of injuries and decreasing the stress caused by the performance of repetitive tasks.

3.6.3 Development of a Simulation Model

It is important to mention that the simulation study described in this document is not complete. As sawn before, the simulation study still needs a few steps before its complete, such as the verification and validation, a sensivity analysis, a design of experiments and the respective outputs and, to end, an implementation proposal.

Although the simulation model that currently exists already can model the real scenario of the workspaces in focus, the data used is not valid, since the robot performance indicators have not yet been tested, as they're yet not ready. Therefore, the simulation study can't move forward for now. Once the robot is tested, and performance data is available, the simulation study shall continue for the mentioned steps, so at end, could be able to provide important information on SP's decisions for the HRC implementation such as Resource Allocation and Production Planning.

Afterwards, the simulation model entities regarding the three different types of products that we might have in the line, should be replaced by each product itself, with concrete tasks and times associated with it. Once, this task is done, it will be possible to simulate and test, different production orders sequences to find the best framework to optimize the production line and the utilization of both robotic and human resources.

Chapter 4: Conclusions

In the days that we currently live in, there is almost absolutely no doubt that these are times of change. Industry 4.0 is no longer a mirage on the horizon or a trending topic but rather a reality, and companies should be quick and able to adapt their processes to this new paradigm with the risk of being obliterated by the competition in a short range of time.

In Portugal's current industry scenario, the concept of smart factories is still yet to be explored, but Portuguese companies should not ignore these new technological advancements and embrace innovation, not just for its corporate benefit but also for the common good of all its stakeholders. The Human-Robot Collaborations cells concept, as we seen in this document, is a new way of thinking, that if sustainably implemented with proper safety conditions, could bring advantages for many sectors in the product lifecycle, such reducing the production lead time and increasing the quality on the finished goods, by removing the human error from tasks by relieving the collaborators of demotivating tasks that historically had resulted in injuries.

Industrial Simulation is also a technology that companies like Simoldes should start focusing on. During the time of the project, the developments made on the simulation models of the project case studies, made the company's responsible realize that Simulation could bring many more advantages and cost savings to the company in other functional areas, specially logistics. From being a quite unknown technology within Simoldes, Industrial Simulation is now being prepared to be used in other company optimization projects and something to be invested on, which reflects the importance that it had on project so far, even if the results are not possible to be shown in this document.

But working in the last months within this project helped understand that the Industry 4.0 path is not something that should be explored alone, and this document proves that. The globalized mindset that is a sign of our times, helped increase the communication between organizations and a better share and flow of knowledge. For example, this work shown that creating bonds between academical and other small and medium enterprises, helped Simoldes, not just to came up with a solution that is expected to create a positive impact in the company, but also, to develop knowledge that will help Simoldes develop other areas in the company and to expand its horizons.

The work developed in this project provided Simoldes a sustainable basis to work on, for the upcoming two years until the planned physical implementation of the human-robot collaboration work cells. Still, has it is involved in a Research and Development project along academic and investigation partners, it is most important that Simoldes should constantly be updated on each development as this work should be constantly reviewed.

To conclude this document from where it started, this new Industrial Revolution is already in motion, and it cannot be stopped, but something must clear. Although many fear that this uncontrolled and wild development on technology, that every day comes up with a new process innovation, is the main trigger of a revolution and will eventually throw people out to unemployment and having business running on their own, is wrong. The human individual is and should always be trigger of a revolution since it will always be impossible to remove the human factor out of the productive process. The well-being of every stakeholder from suppliers to clients, passing through the collaborators, should always be the main engine for a successful Industry 4.0 implementation. If a company's culture doesn't adapt to it or the collaborators, clients or suppliers doesn't engage with it the implementation is condemned to failure, resulting in serious consequences for the whole company.

Technology might relieve us from the most demanding jobs, but like the popular singer James Brown used to sing, this will always be a Man's world.

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Appendix I: Human-Robot Task Allocation for the Complex Assembly Lines

Seat Ibiza				
Order	**Task**	**Human**	**Robot**	**Auxiliary Equipment**
1	Plastic Part & Puffer			
1.1	Fetch plastic part	x	x	-
1.2	Visual inspection	x	?	-
2	Puffer			
2.1	Fetch puffer	x	x	-
2.2	Insert puffer into the plastic part	x	?	-
2.3	Place plastic part in the auxiliary equipment	x	x	-
3	Spring			
3.1	Fetch spring	x	?	-
3.2	Insert spring into the plastic part	x	-	-
4	Handle			
4.1	Fetch handle	x	x	-
4.2	Place handle into the plastic part (minding the spring)	x	-	-
5	Rod			
5.1	Compress plastic part, handle and spring	-	-	x
5.2	Fetch rod	x	x	-
5.3	Place rod in the auxiliary equipment at the correct orientation	x	x	-
5.4	Insert rod through spring, plastic part and handle	-	-	x
6	Handle inspection			
6.1	Handle force inspection	-	x	x
7	Packing			
7.1	Insert part into plastic bag	x	x	-
7.2	Palletized packing	x	x	-

T-ROC				
Order	**Task**	**Human**	**Robot**	**Auxiliary Equipment**
1	Handle			
1.1	Fetch handle	x	x	-
1.2	Place handle in the auxiliary equipment	x	x	-
1.3	Visual inspection	x	?	-
2	Bushing			
2.1	Fetch Bushing	x	x	-
2.2	Place Bushing in the auxiliary equipment	x	x	-
3	Puffer, Plastic Part & LED (optional)			
3.1	Fetch puffer	x	x	-
3.2	Fetch plastic part	x	x	-
3.3	Insert puffer into the plastic part	x	?	-
3.4	Place LED in the plastic part (optional)	x	-	-
3.5	Place plastic part in the auxiliary equipment	x	x	-
4	Spring			
4.1	Fetch spring	x	?	-
4.2	Insert spring into the plastic part	x	?	-
5	Rod			
5.1	Compress plastic part, handle, CASQUILHO and spring	-	-	x
5.2	Fetch rod	x	x	-
5.3	Place rod in the auxiliary equipment at the correct orientation	x	x	-
5.4	Check LED light (optional)	x	x	-
5.5	Insert rod through spring, plastic part and handle	-	-	x
6	Handle Inspection			
6.1	Handle force inspection	-	x	x
7	Packing			
7.1	Insert part into plastic bag	x	x	-
7.2	Palletized packing	x	x	-

VW Polo				
Order	**Task**	**Human**	**Robot**	**Auxiliary Equipment**
1	Handle			
1.1	Fetch handle	x	x	-
1.2	Place handle in the auxiliary equipment	x	x	-
1.3	Visual inspection	x	?	-
2	Puffer, Plastic Part & LED (optional)			
2.1	Fetch puffer	x	x	-
2.2	Fetch plastic part	x	x	-
2.3	Insert puffer into the plastic part	x	?	-
2.4	Place LED in the plastic part (optional)	x	-	-
2.5	Place plastic part in the auxiliary equipment	x	x	-
3	Spring			
3.1	Fetch spring	x	?	-
3.2	Insert spring into the plastic part	x	?	-
4	Rod			
4.1	Compress plastic part, handle and spring	-	-	x
4.2	Fetch rod	x	x	-
4.3	Place rod in the auxiliary equipment at the correct orientation	x	x	-
4.4	Check LED light (optional)	x	x	-
4.5	Insert rod through spring, plastic part and handle	-	-	x
5	Handle Inspection			
5.1	Handle force inspection	-	x	x
6	Packing			
6.1	Insert part into plastic bag	x	x	-
6.2	Palletized packing	x	x	-

Appendix II: Multi Product Line Case Study Post Injection Task Sequence and Respective Times

Machine	Mould	Task	Time(sec)
KM 80-I	MO.7249	Fetch piece from the convoyer and analyse it according to the Control sheet	2
		Pack piece according to the Packing Sheet	2
		If first piece, place a label in the container	0,1
		If last piece, place Poka-Yoke label in the container's interior lateral side and proceed to its read	0,1
		Repete previous operation sequence for the opposite side pieces	4,2
		Perform injection control hourly, and regist it	0,1
		Total Time	8,4
EN 110-1	MO.7480	Fetch piece from the convoyer and analyse it according to the Control sheet	6
		Pack piece according to the Packing Sheet	6
		Perform injection control hourly, and regist it	0,1
		If first piece, place a label in the container	0,01
		Total Time	12
	MO. 8238	Fetch pieces from the convoyer and analyse it according to the Control sheet	3
		Pack piece according to the Packing Sheet	2
		If first piece, place a label in the container	0,02
		Repete previous operation sequence for the opposite side pieces	5
		Perform injection control hourly, and regist it	0,01
		Total Time	10,1
KM 200-IV	MO. 6913	Fetch piece from the convoyer and analyse it according to the Control sheet	4
		Place sponge component in the piece	5
		Place traceability label on sponge component	2
		Pack piece according to the Packing Sheet	3
		Perform injection control hourly, and regist it	0,004
		If first piece, place a label in the container	1,04
		Total Time	15,04
	MO. 8265	Insert 2 Nut Push on Auxiliary Equipment	3
		Fetch piece from the convoyer and analyse it according to the Control sheet	2
		Mount 3 sensor bracket (just for ref. F03314013003A)	14
		Place piece on auxiliary equipment and press Start	3
		Screw 2 bolts on piece	14
		Fetch piece from auxiliary equipment and place traceability label	2
		Pack piece according to the Packing Sheet	5
		If first piece, place a label in the container	1
		Total Time without Bracket	31
		Total Time with Bracket	45
	MO. 8428	Fetch piece from conveyor and remove the sprue	2
		Analyse piece conformity according to the Control Sheet	2
		Use device with sandpaper P1000 in piece extremities	12
		Pack piece according to the Packing Sheet	4
		Repete previous operation sequence for the opposite side pieces	20
		If first piece, place a label in the container	0,2
		Total Time	40

Machine	Mould	Task	Time(sec)
KM 200-V	MO. 7103	Fetch piece from the convoyer and analyse it according to the Control sheet	4
		Pack piece according to the Packing Sheet	3
		If last piece, place Poka-Yoke label in the container's interior lateral side and proceed to its read	0,15
		Repete previous operation sequence for the opposite side pieces	7,15
		If first piece, place a label in the container	0,73
		Total Time	15
	MO. 7640	Fetch piece from the convoyer and analyse it according to the Control sheet	3
		Place Clip, Goujon and Foam EPDM on piece	10
		Place piece on auxiliary equipment	3
		Mark the components	3
		Pack piece according to the Packing Sheet	3
		If last piece, place Poka-Yoke label in the container's interior lateral side and procee	0,35
		Perform injection control hourly, and regist it	6
		If first piece, place a label in the container	1,6
		Total Time	30
KM 200-III	MO. 8611	Fetch piece from the convoyer and analyse it according to the Control sheet	9
		Pack piece according to the Packing Sheet	4
		Perform injection control hourly, and regist it	0,003
		If first piece, place a label in the container	0,5
		Total Time	13
	MO. 8491	Fetch piece from the convoyer and analyse it according to the Control sheet	
		Pack piece according to the Packing Sheet	3
		If first piece, place a label in the container	1
		Perform injection control hourly, and regist it	1
		Total time	5
EN 225 - II	MO. 6830	Fetch piece from the convoyer and analyse it according to the Control sheet	4
		Pack piece according to the Packing Sheet	4
		Perform injection control hourly, and regist it	0,1
		If first piece, place a label in the container	1
		Total Time	9
	MO. 7793	Fetch piece from the convoyer and analyse it according to the Control sheet	4
		Pack piece according to the Packing Sheet	4
		Repete previous operation sequence for the opposite side pieces	8
		Total Time	8
	MO. 8537	Fetch piece from the convoyer and analyse it according to the Control sheet	4
		Pack piece according to the Packing Sheet	6
		Perform injection control hourly, and regist it	0,1
		If first piece, place a label in the container	0,5
		Total Time	11

Appendix III: Car Door Handle Tasks Time Table

SEAT IBIZA	Inspection	Puffer	Spring	Handle	Packing	TOTAL
1	5	5,4	3,8	4,8	5,6	24,6
2	3,7	3,2	2,6	2,9	3,6	16
3	3,3	3	4,5	2,2	5	18
4	4	5,4	3,5	3,2	4,8	20,9
5	3,6	4,2	3,2	3,3	3,5	17,8
6	4,8	3,5	2,3	2,3	3,6	16,5
7	4,9	4	2,9	3,7	3,5	19
8	4,8	2,7	3,4	5,4	4,9	21,2
9	4,2	4,1	3,1	3	3,3	17,7
10	6,2	3,5	4	3,5	4,6	21,8
Minimum	**3,3**	**2,7**	**2,3**	**2,2**	**3,3**	**16**
Average	**4,5**	**3,75**	**3,3**	**3,25**	**4,1**	**18,5**
Maximum	**6,2**	**5,4**	**4,5**	**5,4**	**5,6**	**24,6**

VW T-ROC	Inspection	Bushing	Handle	Puffer	Spring	Packing	TOTAL
1	4,3	4	2,8	4,6	2	4,4	22,1
2	3,8	4	2	4,1	1,7	3,9	19,5
3	5,2	4	4	3,7	4	4,6	25,5
4	5,7	4	2,3	5,6	3,1	4,8	25,5
5	4,3	4	2,1	6	2,3	3,7	22,4
6	3,8	4	2,3	5,3	2,6	3,5	21,5
7	5,4	4	3	3,4	3	3,8	22,6
8	6	4	2,2	3,4	2,9	4,7	23,2
9	4,8	4	4,6	4,4	2	3,6	23,4
10	5	4	2	3,7	2,6	4,3	21,6
Minimum	**3,8**	**4**	**2**	**3,4**	**1,7**	**3,5**	**19,5**
Average	**4,9**	**4**	**2,3**	**4,25**	**2,6**	**4,1**	**22,5**
Maximum	**6**	**4**	**4,6**	**6**	**4**	**4,8**	**25,5**

VW POLO	Inspection	Handle	Puffer	Spring	Packing	TOTAL
1	4,3	2,8	4,6	2	4,4	18,1
2	3,8	2	4,1	1,7	3,9	15,5
3	5,2	4	3,7	4	4,6	21,5
4	5,7	2,3	5,6	3,1	4,8	21,5
5	4,3	2,1	6	2,3	3,7	18,4
6	3,8	2,3	5,3	2,6	3,5	17,5
7	5,4	3	3,4	3	3,8	18,6
8	6	2,2	3,4	2,9	4,7	19,2
9	4,8	4,6	4,4	2	3,6	19,4
10	5	2	3,7	2,6	4,3	17,6
Minimum	**3,8**	**2**	**3,4**	**1,7**	**3,5**	**15,5**
Average	**4,9**	**2,3**	**4,25**	**2,6**	**4,1**	**18,5**
Maximum	**6**	**4,6**	**6**	**4**	**4,8**	**21,5**

Appendix IV: Pieces Injection Cycle Times

Machine	Piece	Time (sec)		
		Mín	Med	Máx
KM 80-I	MO. 7247	25	26	27
	MO.7249	24	25	26
	MO. 8536	31	33	33
	MO. 7833	26	27	28
	MO. 8112	24	25	26
	MO.8220	33	34	35
	MO. 8487	24	26	26
	MO. 8535	37	39	39
EN 110-I	MO. 7480	28	29	30
	MO. 7503	28	30	31
	MO. 8238	29	31	31
	MO. 8491	26	28	28
	MO. 8534	30	32	32
KM 200-IV	MO. 6913	35,9	37	38,1
	MO. 7017	29	30	31
	MO. 8265	34	35	35
	MO. 8428	43	45	45
	MO. 8463	43	45	45
KM 200-V	MO. 7029	34,9	36	37,1
	MO. 7103	35	37	37
	MO. 6568	37,8	39	60,2
	MO. 7640	42,7	44	45,3
	MO. 7717	31	32	33
	MO. 7819	29	30	31
	MO. 8080	36,9	38	39,1
KM 200-III	MO. 7534	29	30	31
	MO. 7847	39	40	41
	MO. 8600	36	38	38
	MO. 8611	34,9	36	37,1
	MO. 8816	38	40	40
EN 225-II	MO. 6830	30	32	32
	MO. 7793	35	37	37
	MO. 8537	32	34	34